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**A 2000-HOUR DURABILITY TEST OF A 5-CENTIMETER  
DIAMETER MERCURY BOMBARDMENT ION THRUSTER**

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**A 2000-HOUR DURABILITY TEST OF A 5-CENTIMETER DIAMETER  
MERCURY BOMBARDMENT ION THRUSTER**

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**SUMMARY**

A 2000-hour durability test of a modified Hughes SIT-5 (Structurally Integrated Thruster, 5 cm) was conducted at the Lewis Research Center. The thruster operated with a translating screen thrust vector grid locked in position for  $10^0$  beam deflection. The test was essentially continuous except for seven stoppages of beam current. The neutralizer keeper voltage and thruster floating potential increased slightly with time.

Performance profiles and maps of thruster characteristics were obtained at 453 and 2023 hours into the test. Overall efficiency was nearly constant at 31 - 32 percent, and operating characteristics were similar at both points in the test.

A post-shutdown inspection showed negligible erosion damage to the accelerator and cathode baffle. Some erosion was found in the aperture of the neutralizer cathode.

## INTRODUCTION

Electrostatic ion thrusters have potential application for spacecraft attitude control and station-keeping functions on a variety of missions (refs. 1, 2, and 3). Primary requirements for such thrusters are reliability and durability. Thrust vectoring capability is also desirable for many applications (ref. 4).

Extensive research and development have been conducted at the NASA Lewis Research Center and elsewhere on 5-centimeter diameter electron bombardment ion thrusters (refs. 5, 6, and 7). The design and development of a thrust vectorable structurally integrated thruster system (SIT-5) has been performed by Hughes Research Laboratories under NASA Contracts NAS3-14129 and NAS3-14058.

This report presents the results of the first increment of an on-going test of the SIT-5 thruster operated at near steady-state conditions for over 2000 hours. The test was conducted with open-loop fixed point power inputs to the thruster. High-low limit switches, however, protected the thruster from sustained abnormal operating conditions. The variation of thruster operating characteristics is shown in an abridged time history of the test. Typical thruster performance profiles from early in the test are compared with those at the end of the test. The effects of varying thruster parameters about the steady-state operating point are given. Photographs of various thruster components after the test shutdown are included.

## APPARATUS

### Hughes SIT-5 Thruster System

A sectional view of the Hughes SIT-5 thruster system as delivered is shown in figure 1. The thruster is a mercury Kaufman-type using a permanent magnet field. The main cathode, isolator, and main vaporizer are integrated into a CIV subassembly. The isolator allows the propellant feed system to remain at spacecraft potential while the thruster operates at positive high voltage. The entire propellant flow

to the ion chamber is fed through the enclosed keeper hollow cathode. A vented pole piece and baffle assembly designed for post-cathode propellant diversion is utilized to optimize performance and to obtain the desired ion chamber discharge volt-ampere characteristics.

The neutralizer cathode and its vaporizer are integrated into an NV (neutralizer-vaporizer) subassembly. The neutralizer cathode is also an enclosed keeper-type with a rolled foil insert, designed to operate at mercury flow rates below 2.5 mA equivalent  $\text{Hg}^+$ . Further description and design details of the SIT-5 system may be found in reference 7.

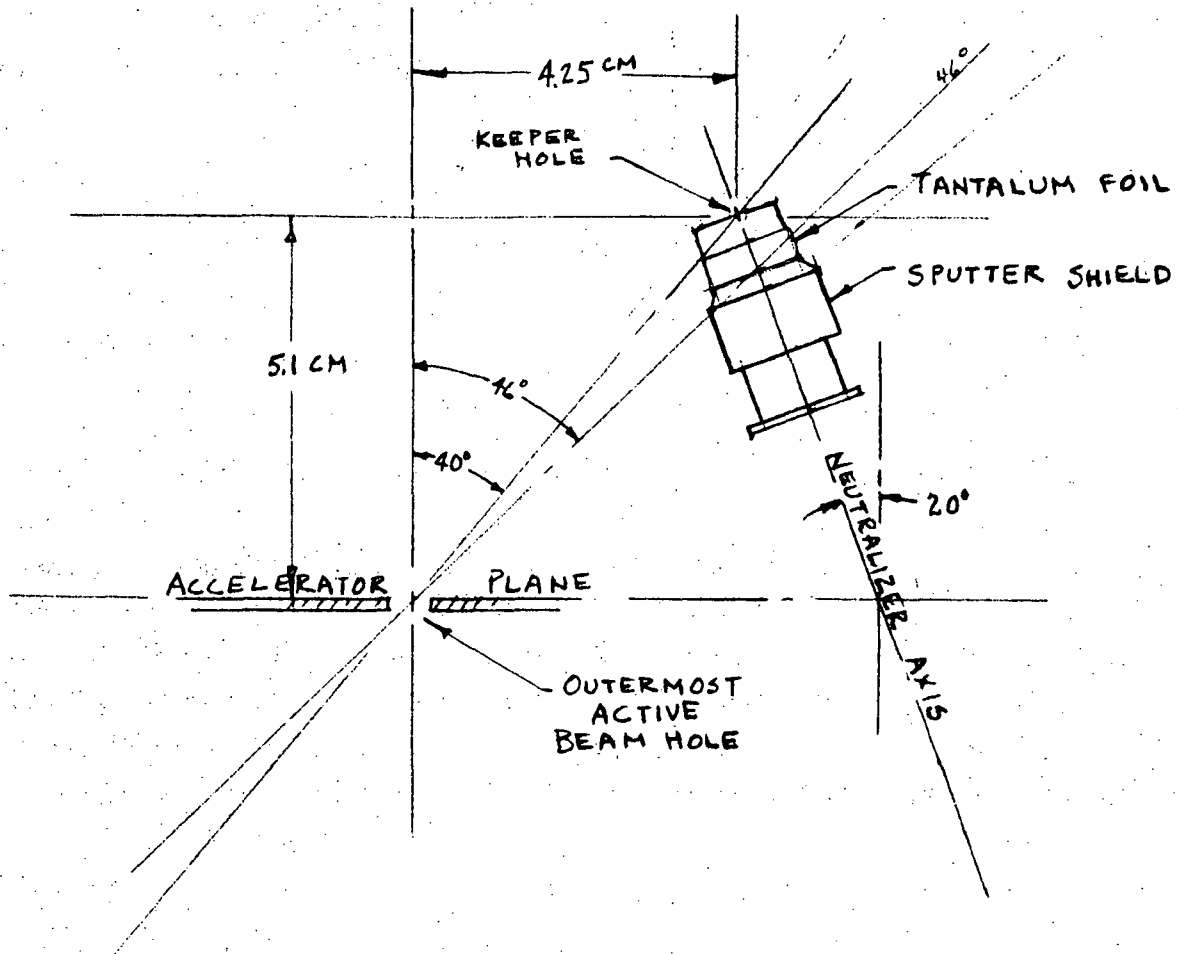
### Test Installation

Figure 2 shows the test installation of the SIT-5 thruster system modified to meet specific requirements of the durability test conducted at the Lewis Research Center. In order to permit independent measurements of the propellant flow rates, the SIT-5 propellant reservoir was removed and the main cathode and neutralizer were connected to capillary tube flow meters.

Seven permanent magnets were used for testing with the thrust vectoring optics. This decision was based on previous experience with thruster operation at a beam current of 25 mA, the current level selected for the present test.

A translating screen thrust vectoring system (ref. 8) was used. This system permits translation of the screen grid with respect to the fixed accelerator grid in a plane perpendicular to the thruster axis. A relative misalignment of the grid holes produces a deflected beam. Design details and performance of this thrust vectoring system are given in reference 9. For the present test, the grid was mechanically locked with a misalignment of 0.32 mm to deflect the beam approximately 10 degrees in a direction perpendicular to the neutralizer. The inside diameter of the downstream ground screen mask was enlarged to 6.05 cm diameter to avoid interception of the deflected beam.

The neutralizer was mounted outboard of the thruster and isolated from the facility ground. Details of the neutralizer position are shown in sketch (a).



Sketch (a)

This position and orientation was used to reduce the fall-back of low velocity neutralizer plasma ions onto the accelerator (ref. 10). The axis of the neutralizer was inclined 20 degrees toward the thruster axis, and the keeper aperture was positioned 5.1 cm downstream and 4.25 cm radially out from the outermost active beam hole of the accelerator. An extended sputter shield was attached to the neutralizer keeper to protect its ceramic insulator.

The two rectangular boxes visible in figure 2 are contaminant collectors. These were mounted as part of an independent study of surface contamination due to sputtered metal and no further reference to them will be made in this report.

### Electrical and Data System

An electrical schematic of the power and data acquisition system is shown in figure 3. The power system had a line voltage regulator to maintain a constant input voltage. The voltage and current ratings of the power supplies are indicated on the schematic. All heater supplies were variable primary ac filament transformers. The cathode keeper was powered by a regulated dc supply having a constant current - constant voltage control characteristic. The control permitted a variable point crossover with negligible output capacitance while in the constant current mode. A separate ignitor supply provided a 500-volt, 100-mA output to the cathode keeper for starting the discharge. Blocking diodes prevented the ignitor supply from feeding power into the cathode keeper supply.

The neutralizer keeper used two dc power supplies in parallel. One supply had a 500-volt, 100-mA output ballasted through a 2000-ohm resistor to function as an ignitor. A regulated dc supply with constant-voltage, constant-current output characteristics and blocking diodes was used as the low voltage neutralizer keeper power supply.

The discharge power supply was a commercial grade regulated dc supply also with a constant-voltage, constant-current automatic crossover output. The net accelerating and accelerator potentials power supplies used in the initial part of the durability test were commercial grade high voltage, precision regulated supplies with automatic crossover between their voltage and current regulation modes. A 5-henry 125 mA choke was used as an inductive ballast on the output of these supplies. The chokes limited transient high voltage breakdown arc currents and improved operational stability of the thruster and neutralizer.

An unexpected failure of the accelerator potential supply during the test required replacement with an unregulated output dc power supply. The constant low current requirements of the accelerator circuit made this substitution satisfactory.

Thruster variables monitored during the test include those which are normally at neutralizer common potential and those which are floated at net accelerating or accelerator potential. All variables at neutralizer potential were scaled to suitable magnitudes by means of voltage dividers or current shunts and monitored directly. Scaled signals from variables at high positive or negative potentials were transmitted to ground potential by means of a frequency modulated light signal. The signal was then demodulated to a suitable dc analog voltage.

All data signals were fed to panel meters on the control console and also to the Central Automatic Digital Data Encoder (CADDE) system of the Lewis Research Center. Use of the CADDE system permitted automatic data acquisition at clocked intervals and at off-normal thruster operating conditions. The data thus acquired could be typed back to the test facility in engineering units and/or processed by computers to calculate performance. The overall accuracy of digitized data is 1 percent. Data obtained by the panel meters are typically accurate to 3 percent of full scale reading. Test hours were logged on a digital meter with a least reading of 0.1 hours. The hour meter was wired to stop whenever the thruster shut down. A protective control system consisting of meter relays, timers, and multicontact relays was utilized for unattended operation of the thruster. The purpose of the control logic was to detect off-normal operation of the thruster or vacuum facility and to shut down the thruster if a potentially damaging condition existed beyond a preset time interval. The operating variables which could activate the protective control logic were: (1) high or low beam current, (2) high accelerator drain current, (3) high thruster floating potential, and (4) high vacuum facility pressure. Any one of the off-normal conditions also initiated a data scan on the CADDE system to

record thruster variables. In the event of a shutdown, a diagnostic light indicated the cause of the shutdown.

### Test Facility

A photograph of the test facility is shown in figure 4. The vertical console on the far left contains all the power supplies and meters for operating the thruster. The rack to its right contains the meter relays and timers which comprise the protective control logic.

In figure 4 a vacuum facility is visible on the far right. The tank is 1.37 m in diameter and 1.83 m tall. Oil diffusion pumps of 25.4 cm diameter and 40.5 cm diameter maintained a nominal pressure of  $1 \times 10^{-6}$  torr during thruster operation when operated in conjunction with a cryowall and frozen mercury ion beam target.

Figure 5 is a photograph of the tank interior. The stainless steel pan for the target mercury was attached to 12 radial copper struts to which copper cooling coils were brazed. A cylindrical cooling coil brazed to vertical copper strips formed the cryowall which extended along the vertical wall of the tank.

The thruster was operated at a distance of 76.2 centimeters from the frozen mercury target which was 112 centimeters in diameter. To prevent the backspattering of condensible conductive material upon the thruster from the sides of the vacuum facility, in addition to the frozen mercury target, a set of nonmetallic baffles was installed in line of sight of the thruster ion beam. The baffle assembly consisted of three slanted annular baffles spaced 25 cm apart with an 83.8 cm inside diameter opening. The baffles were made from 0.63 cm thick sheets of Fiberfax insulation (50 percent  $\text{Al}_2\text{O}_3$ ; 50 percent  $\text{SiO}_2$ ) fitted and supported on a frame fabricated of stainless steel sheet strips. Care was taken to expose only the frozen mercury target surface or an insulating surface to the ion beam.

## PROCEDURE

### Test Preparation

The following pretest procedures were used after filling the target with liquid mercury and installing the thruster: The vacuum facility was first rough-pumped mechanically to about 100 microns pressure which removed gas bubbles entrained in the mercury fill system or target crevices. Outgassing of these gas pockets appeared as bubbles which escaped at the liquid mercury surface.

The oil diffusion pumps were then turned on to obtain a tank pressure in the neighborhood of  $5 \times 10^{-4}$  torr. At this point, liquid nitrogen was fed to the mercury target.

As the cooling of the target progressed, the tank pressure also decreased. At about  $1 \times 10^{-4}$  torr pressure, the liquid nitrogen was fed to the cryowall. The target contained approximately 265 kg of mercury and required about 4 hours to solidify. With the target frozen and the cryowall at equilibrium temperature, the ultimate tank pressure was generally in the mid- $10^{-7}$  torr range.

### Thruster Startup and Operation

Prestartup preparation included procedures such as vacuum-filling the propellant feedlines and warming up the power system and signal isolators to stable operating temperatures.

Thruster startup was initiated by applying about 20 watts to the heaters of the main cathode and the neutralizer. When the cathode vaporizer temperature reached about  $250^{\circ}\text{C}$  (because of thermal feedback from the cathode heater), power was applied to the vaporizer to attain starting mercury flow rates. Because of the integrated thermal design, the cathode heater also heated the cathode isolator to about  $320^{\circ}\text{C}$ .

which was sufficient to prevent mercury condensation. With an applied keeper voltage of about 500 V, the keeper discharge started when the vaporizer temperature reached the neighborhood of  $350^{\circ}$  C. This temperature corresponded to a mercury flow rate of about 70 mA.

A similar procedure was used to start the neutralizer discharge. In the absence of an isolator, the neutralizer vaporizer heated up more rapidly than the cathode vaporizer. A starting temperature of about  $380^{\circ}$  C was found to be necessary. At this temperature, the mercury flow rate corresponded to about 40 mA.

Both keeper discharges were stabilized by adjusting the vaporizer temperatures to attain the flow rates (determined from previous tests) corresponding to normal thruster operation.

The accelerator and net accelerating potentials were then applied prior to initiating the ion chamber discharge. This procedure avoided the initial upsurge of accelerator drain current during the buildup of the accelerator power supply potential. Simultaneous application of the net accelerating, accelerator, and discharge potential was also tested and allowed stable thruster startup. The relatively smooth startup of the ion chamber with the high potentials already applied, however, and the capability of regulating the initial ion beam current buildup tended to favor the adopted procedure.

Finally, thruster variables were adjusted to obtain stable operation at the selected beam current of 25 mA and maintained throughout the steady-state portions of the durability test. Minor adjustments were made as required to correct for temperature drifts or long-term changes in operating behavior.

Several times during the test, performance maps were obtained by varying a thruster parameter while holding all other variables constant. The ion chamber and neutralizer propellant flow rates were held at about 34 mA and 2.2 mA, respectively.

## RESULTS AND DISCUSSION

This section will first present a narrative review of the steady-state portion of the 2000 hour test, including discussion of any time variation of thruster electrical parameters, propellant flow rates, and thruster shutdowns. The performance profiles and effects of parameter variations at 435 and 2000 hours into the test will be presented. Finally, the results of the post-test inspection will be discussed.

### History of Test

The values of all electrical parameters were monitored throughout the test. Several thruster and neutralizer subsystem parameters are plotted as functions of thruster operating time in figures 6 and 7, respectively. The time scale is not plotted continuously but abridged over those periods when all parameters were essentially constant. Operating periods in which numerous events occurred are plotted to an expanded scale. Uneventful periods such as the latter part of the test are shown on a compressed time scale. For brevity, all the parameters are not shown on these figures. The values and general trends of those parameters not shown are discussed below.

Ion beam current was held constant at  $25 \pm 1$  mA throughout the steady-state portion of the test. Minor day-to-day adjustments were made in the cathode vaporizer temperature to obtain the required beam current with the ion chamber discharge constant-current controlled at nominally 0.26 A. The discharge voltage was very sensitive to cathode propellant flow rate with an inverse relationship of higher discharge voltages at lower propellant flows. Adjustment to the nominal value of 34 mA equivalent flow rate, however, returned the discharge voltage to about 37 volts which prevailed throughout the test.

The net accelerating and accelerator potentials were held at +1010 and -1000 volts, respectively, throughout the test. Day-to-day drift in these

voltages as recorded on the CADDE system was approximately  $\pm 20$  volts. No isolator leakage current was detectable on a 20-microampere, full scale meter over the test duration which indicated that the current was always less than 0.1 microampere. The propellant flow rate to the main cathode was measured once or twice a week and generally fell within  $\pm 2$  mA of the typical 34 mA equivalent flow. The vaporizer temperature was a good indication of reproducible flow rates if maintained within  $\pm 1^\circ \text{C}$  of the nominal  $340^\circ$ . The flow rate variations quoted above were averaged over a period of 4 to 6 hours and momentary rise in vaporizer temperature may have given correspondingly larger deviations than 2 mA per degree. The neutralizer flow rate was held between 2 to 2.3 mA equivalent with a maximum variation of  $\pm 0.5$  mA. Reduction of flow below 1.5 mA caused a rapid increase in neutralizer keeper voltage. Increasing the flow above 2.8 mA caused a rise in thruster floating potential.

At the start of the test, the cathode and neutralizer heater powers were set at 4 and 14.6 watts, respectively. At 2 hours an arc between the accelerator grids extinguished the neutralizer keeper discharge. The resulting high thruster floating potential of over 50 volts activated the protective control logic and caused a general thruster system shutdown. Following this shutdown, the logic was changed so that a neutralizer outage removed the net accelerating and accelerator potentials and the discharge voltage. This change allowed the cathode keeper discharge and any other heater power to remain on, thus permitting a faster restart.

The thruster was restarted without difficulty, and the test continued to 59 hours without a neutralizer outage. During this period the cathode keeper current was adjusted to find conditions which resulted in a lower keeper voltage favorable to cathode life. At about the 33-hour point, with a keeper current of 0.3 A, the keeper voltage was about 12 volts. At 55 hours, the cathode keeper current was reduced to 0.28 A with no appreciable change in keeper voltage. The accelerator drain current was nearly constant at 0.06 mA, and was primarily dependent on neutral flow rate and propellant utilization efficiency. These conditions prevailed up to the 59th hour.

The tendency of accelerator grid arcs to extinguish the neutralizer keeper discharge prompted the operation of the neutralizer with a heater power of 14.6 W and a relatively high keeper current of 0.4 A. At these conditions the keeper voltage remained near 10 volts. Thruster floating potential was generally 10 volts or less negative with respect to facility ground.

In the interest of reducing power requirements, the neutralizer heater power was reduced to 4.7 W and the keeper current to 0.34 A at the 21-hour point. The keeper voltage increased to 15 volts, but the thruster floating potential was acceptably low, and these conditions were maintained with downward adjustments of the keeper current to 0.3 A at 27 hours.

Starting at about the 30th hour, the thruster floating potential became somewhat erratic and at 59 hours, the second neutralizer outage occurred. The thruster did not undergo a general shutdown because of the previously mentioned change in the protective control logic. The neutralizer was restarted and the test was resumed. Adjustments in the keeper discharges during the ensuing 50 hours can be seen in figures 6 and 7. Thruster operation was stable and constant up to the 114th hour when the third neutralizer outage occurred. The data acquisition 1 hour prior to the outage showed no deviation from the conditions prevailing for the previous 20 hours. The last clocked data point one-half hour prior to the outage showed a rise in thruster floating potential to 13.4 volts. Several other parameters showed erratic variations which are believed to be caused by signal noise, possibly due to changing neutralizer operation. The main cathode keeper discharge continued to operate until thruster operation was resumed at 123 hours.

All thruster variables were held essentially constant except for minor drifts up to 377 hours at which time the heater power of both the main cathode and neutralizer were reduced to zero. In order to prevent a considerable rise in cathode keeper voltage, the cathode keeper current was increased to 0.32 ampere. The slight increase in keeper discharge

power apparently compensated for the removal of heater power and the keeper voltage stabilized at 12 volts, an increase of about 2 volts. The neutralizer keeper voltage similarly increased 2 volts.

The thruster then ran until 874 hours with no difficulty. During this period two malfunctions of the vacuum facility caused perturbations in the tank pressure at 625 and 752 hours. The latter pressure increase was sufficient to cause a facility and thruster shutdown. The thruster was unaffected by the over-pressure conditions.

At 874 hours another thruster shutdown occurred. The indicator lights showed that both high floating potential and low beam current conditions had existed previous to the stoppage. Inspection indicated a malfunction in the current regulator circuit of the cathode keeper, which may have caused unstable thruster operation. Unfortunately, there was also a malfunction in the weekend standby data acquisition system, and detailed data prior to the shutdown was not obtained.

The thruster system was intentionally shut down to repair the cathode keeper current regulator. After resumption of the test, the cathode keeper current was readjusted, and the neutralizer heater power was raised to 4.8 watts until the 896 hour point at which it was reduced to zero. Normal operation continued until 1000 hours at which time the thruster floating potential began to rise gradually over a 24-hour period. At 1024 hours, an increase in thruster floating potential above the protective control limit caused a thruster beam shutoff. A gradual drop in the neutralizer keeper current and rise in keeper voltage was recorded over the same period, and may be indicative of changing neutralizer operation.

The thruster operation was resumed, but with the neutralizer heater off, an increase in neutralizer keeper current to 0.45 A was required to provide stable floating potential operation. The neutralizer keeper voltage was 16 volts, essentially the same as earlier in the test. However, small step changes were observed in the keeper voltage and the thruster floating potential as if the neutralizer discharges were changing mode or shifting to a different point on its

characteristic volt-ampere curve. The shift was only temporary inasmuch as the parameters restabilized to their former values within a few minutes. In addition, slow oscillatory drifts in neutralizer vaporizer temperatures were also detected, which may have contributed to the shifts in neutralizer operation. In an effort to eliminate the shifts in the neutralizer keeper discharge, 3 watts of heater power was supplied at the 1075-hour point. This helped to reduce the neutralizer keeper voltage to 15 volts.

Between the 1075-hour point and end of test the thruster operation was without incident except for an accelerator power supply failure at 1480 hours. After installing a substitute accelerator power supply, the thruster was restarted without difficulty and the test continued to its conclusion. Over the final 800 hours of the test, a gradual rise in the neutralizer keeper voltage was observed from 15 volts to 18.2 volts. Correspondingly, the thruster floating potential rose from 9 to 11 volts. The cause of this gradual change is not definitely known. The neutralizer heater power was maintained at 3 watts during this period and the keeper current was kept constant at 0.45 A.

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### Performance Profile

Stable operation performance profiles evaluated at the 455 and 2023-hour operating points are shown in tables I and II, respectively. The beam power was the established 25 watts at each point. The total input power was about 3.7 watts higher at the end of test, mostly due to additional neutralizer power. The resulting power efficiency was 3 percent lower at the end, but a slightly higher propellant utilization efficiency brought up the final overall efficiency to within a percent of the early profile. The difference in propellant utilization efficiency corresponds to 1.4 equivalent mA of propellant flow, a quantity which is extremely difficult to preset. The slight increase in discharge losses is attributed to the high utilization efficiency toward the end of test.

### Parameter Variations

The durability test was run essentially at a single fixed operating point and normally did not permit an examination of how thruster operation varied off the set point. To provide a limited mapping of thruster characteristics and to observe any changes in these characteristics with operating time, each parameter was varied over a range of values while holding the remaining parameters constant. The results of these variations obtained at the 455 and 2025 hour points are presented.

Cathode keeper current. - The effects of varying cathode keeper current while holding the beam current at 25 mA and all other input variables constant are shown in figure 8. No cathode heater power was used. Propellant flow was held constant, and any variation in beam current with changes in keeper current was corrected by adjusting the discharge current. Both the 455 and 2025 hour points are shown for comparison.

The keeper voltage at end of test was 2.5 to 3.5 volts higher than at 455 hours. Part of this increase is probably caused by the slightly lower propellant flow rate obtained near the end of test. The higher discharge current required to obtain the 25 mA beam current tends to support this. At the end of test, the digital data acquisition system used to record the data points in quick succession was not recording the discharge voltage accurately and only a single point, obtained manually, is plotted in figure 8. The value of discharge voltage for this point also was slightly higher than at 455 hours.

Discharge current. - The effects of varying discharge current is shown in figure 9. The keeper current was maintained between 0.3 and 0.32 A. No cathode heater power was used. Variation of discharge current produced a strong change in ion beam current. The 2025 hour points were slightly below those at 455 hours, probably because of the slightly lower propellant flow rate (fig. 9(a)). The beam current appeared to have a maximum and was not a monotonic function of the discharge current above 0.3 A.

The variation of accelerator drain current, figure 13(b) with discharge current is a reflection of the accompanying change in beam current. At high discharge currents the high beam current and propellant utilization efficiency reduced the charge exchange ion drain current. At lower discharge and beam currents, the drain current increased to a maximum and then decreased because the formation of charge exchange ions is a function of both the neutral density and the beam current density. The discharge voltage increased almost linearly with discharge current (fig. 9(c)). The value of discharge voltage at end of test was slightly higher because of the lower propellant flow.

The variations in thruster floating potential with discharge and beam current (fig. 9(d)) were similar at both points of the test. The difference in levels was the result of the gradual rise in floating potential described in the history of the test.

Accelerator potential. - The effects of varying the accelerator potential over a range from 500 to 1200 volts are shown in figure 10. The net accelerating potential was held constant at 1010 volts and the beam current was set to near 25 mA for each point by adjusting the discharge current. The variations in drain current are shown in figure 10(a) for the 455 and 2025 hour points. The drain current showed the same trend with accelerator potential at both points in the test.

The variations in discharge current with accelerator potential is shown in figure 10(b). The higher values of the 2025 hour points are indicative of the lower propellant flow. The increase in discharge current with decrease in accelerator potential occurs because the reduced ion extraction necessitates a higher discharge current to obtain the required beam current. The thruster floating potential (fig. 10(c)) was nearly independent of accelerator potential at both points of the test.

Net accelerating potential. - The effects of varying the net accelerating potential with the accelerator potential held at -1000 volts and the beam current near 25 mA are shown in figure 11. The accelerator

drain current (fig. 11(a)) varied only slightly with net accelerating potential both early and late in the test. Apparently, for the current densities existing, direct ion impingement was only a small portion of the total drain current over the range of accelerator voltage tested. The higher utilization efficiency of the 2025 hour points accounts for the lower drain current level.

The variations in discharge current shown in figure 11(b) for early in the test were as expected. Increased ion extraction with increasing net accelerating potential would naturally result in less discharge current to obtain the required beam current. At the end of test, however, increasing the net accelerating potential did not cause a similar decrease in discharge current. At reduced potentials the extent of obtained data indicates a rising trend in discharge current similar to that obtained at the 455 hour point.

The thruster floating potential was nearly constant over the range of variation in net accelerating potential. At the end of the test the floating potential was about 0.3 volt higher than at the beginning.

Net accelerating potential with constant total voltage. - The effects of changing net accelerating potential while also adjusting the accelerator potential to maintain a constant total voltage drop of 2010 volts is shown in figure 12. This variation was done only at the 455 hour point. The accelerator drain current (fig. 12(a)) decreased with increasing net accelerating potential (or decreasing accelerator potential). In view of the relatively small effect of net accelerating potential on drain current of the 455 hour points (fig. 11(a)), the decrease seen in figure 12(a) may be associated with the slight decrease found earlier in figure 10(a) when the accelerator potential was reduced.

The discharge current shown in figure 12(b) was relatively constant over the range of variation in net accelerating potential with a constant total voltage, it is assumed that ion extraction effects were also relatively constant. Thruster floating potential was also invariant with changes in net accelerating potential.

Neutralizer keeper current. - The effects of varying neutralizer keeper current are shown in figure 13. The thruster beam current

was held constant as were also all other thruster variables except the neutralizer keeper voltage and thruster floating potential which were dependent upon the neutralizer keeper current.

At the 455 hour point where no heater power was used, the thruster floating potential was about 9 volts at keeper currents above 0.36 A. A sharp rise in floating potential was observed as keeper current was reduced.

At the 2025 hour point, neutralizer flow rate was the same as before, but 3 watts of heater power was used. As keeper current was reduced from 0.5 to about 0.25 A, a gradual rise in floating potential was observed with a steep rise at lower keeper currents. The steady floating potential at the end of test was about 2 to 3 volts higher than at the 455 hour point. The range of operation with floating potential below 20 volts, however, was extended to lower keeper currents with the addition of heater power.

The neutralizer keeper voltage obtained at two points in the test are shown in figure 13(b). At the end of test, the keeper voltage was generally higher. This is consistent with the gradual rise in neutralizer keeper voltage which was evident in the time history of the test from about the 1100 to 2025 hour (fig. 7).

### Post-Shutdown Inspection

At the conclusion of the test, a detailed inspection and photographic documentation of the thruster system and test facility was performed. The entire thruster was noticeably clean and free of backspattered condensable metal. Details of particular thruster components are given below.

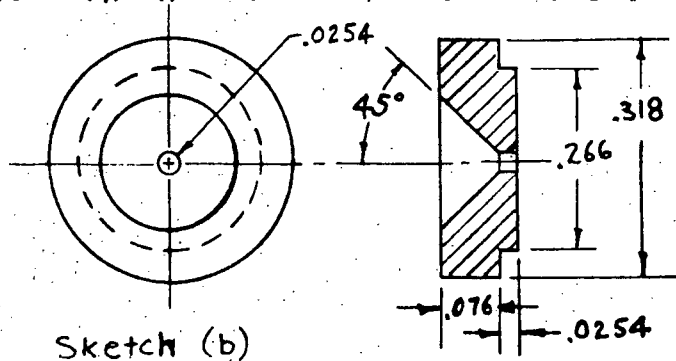
Accelerator grids. - A front view of the accelerator is shown in figure 14. The web region between the grid holes were free of the usual charge exchange ion erosion pits. A ring of pits was found beyond the hole pattern following the contour of the ground screen mask. It is

believed that low energy ions were being focused by the electrostatic field in the mask-to-accelerator region and accelerated into the -1000 volt potential surface. A more detailed discussion of this accelerator system is given in reference 11. Based on the erosion over 2000 hours, a useful life of 20,000 hours is projected.

Neutralizer. - Figure 15 is a closeup view of the neutralizer assembly. There was only minimal evidence of erosion on the 0.05 mm thick sputter shield. A narrow band of 0.025 mm thick tantalum foil used to hold the sputter shield showed sputter erosion in several places (fig. 15). It is concluded that the edge of the sputter shield which falls on a line drawn from the outermost active beam hole at an angle of  $46^\circ$  with the thruster axis, was intercepting the fringe of the ion beam (sketch (a), APPARATUS). Inspection showed that the neutralizer keeper was essentially free of sputter erosion or arc damage. A small hairline crack was found in the ceramic insulator. This crack was probably formed during the swaging operation of the keeper assembly fabrication.

A closeup photograph of the neutralizer cathode tip is shown in figure 16. Microphotographs of the cathode orifice at 7.5, 15, and  $52.5\times$  magnifications are shown in figure 17. The cathode aperture design details are shown in sketch (b). The chamfered surface showed

Note: All dimensions in centimeters



some erosion particularly at the junction of the chamfer and the 0.0254 cm diameter cylindrical hole. It is difficult to tell whether or not the erosion extends the full thickness of

the thoriated tungsten disk. Scaling from the known 0.318 cm diameter cathode tip, the cathode aperture appears to be about 0.0254 cm in diameter (original aperture was 0.0254 cm diam). This would indicate that at least a portion of the original cylindrical aperture still exists.

The detailed mechanism of this erosion is not clear. Because of the enclosed configuration of the keeper design, direct impingement of energetic beam ions upon the neutralizer cathode would be unlikely. Low energy ambient or charge exchange ions can drift to the neutralizer region and be attracted to the neutralizer cathode which is negative with respect to the thruster. Relative to the ion beam plasma potential, the neutralizer keeper also carries a negative potential, and thus should attract ions. Close inspection showed practically no evidence of ion erosion around the neutralizer keeper hole. Any ion falling to the neutralizer cathode would need to be more highly focused than is probable with the existing electrostatic fields.

Some observations from the SERT II hollow cathode tests (ref. 12) indicate that cathode aperture erosion may not be continuous. Starting from a cylindrical hole, the aperture eroded to a tapered hole which apparently fit the geometrical requirements of the discharge. No further erosion was encountered beyond the equilibrium configuration. Observations to date on the continuing test seem to indicate, at least, that failure is not imminent.

Cathode baffle and keeper. - Figure 18 is a closeup photograph of the baffle assembly mounted on the cathode cup pole piece. The SIT-5 design used a size 0 - 80  $\times$  0.635 cm long stainless steel machine screw to facilitate longitudinal adjustment of the baffle position relative to the pole piece. The tip of the screw was eroded to almost the root of the threads. In the final design where adjustment is no longer necessary, the screw may be eliminated entirely. The dark hole in the hexagonal nut holding the baffle is for a safety lock wire, and is not a result of erosion. Some sputtering erosion due to ion bombardment of the baffle assembly can be seen, however, on the edges of the hexagonal nut. The discharge voltage was approximately 37 volts for the duration of this test.

Cathode. - A closeup photograph of the main cathode tip is shown in figure 19. No erosion was evident on the radiation shield which surrounds the cathode tube. The cathode aperture design is identical to that used for the neutralizer. In contrast to the neutralizer, the cathode aperture showed no erosion.

Figure 20 is a photograph of the tank interior taken immediately after removal of the thruster. The mercury target was kept frozen and the facility was brought up to atmospheric pressure with nitrogen to avoid frosting. The camera was positioned as nearly as possible in line with the axis of the facility. A small pit in the target surface marks the exact center of the facility and the target. The light portion of the target indicates the approximate boundary of the impacting ion beam and hence denotes the degree of beam deflection. The 14.8 cm offset at the target plane, 76.2 cm from the accelerator, indicates an 11 degree deflection of the ion beam. This agrees reasonably well with the expected 10 degrees deflection due to the 0.32 cm misalignment of the grid holes.

#### CONCLUDING REMARKS

The initial 2000 hours of an on-going durability test of a 5-cm diameter mercury bombardment thruster has been completed with seven stoppages of beam current or thrusting operation. Three of the stoppages were attributable to extinctions or outages of the neutralizer discharge within the first 150 hours of the test. Two stoppages were due to facility and power supply problems. The exact causes of the remaining two stoppages are not clear. The test was conducted with open-loop fixed point power inputs to the thruster and high-low limit switches for protective control. Closed-loop controllers which would probably be used in a flight type power processor should continuously adjust thruster operation and thus avoid some of the stoppages encountered in the present test.

Minor adjustments to several of the thruster operating parameters were helpful to maintain smooth operation, to minimize input power requirements, and to compensate for temperature drifts in the propellant vaporizers.

Over the duration of the test, cathode and neutralizer discharges restarted easily with no indication of progressively difficult starting. The high voltage propellant feed isolator encountered no breakdown or rise in leakage current. Accelerator drain current remained essentially constant over the duration of the test.

Post-shutdown inspection showed negligible erosion damage to the accelerator and cathode baffle. Some erosion was found in the aperture of the neutralizer cathode, but catastrophic failure does not seem imminent according to the continuing test.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, October 4, 1972.

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**TABLE I. - PERFORMANCE PROFILE**  
**[453 Hours]**

Beam power (corrected for thruster floating potential), W		25.0
Discharge power, W		8.7
Accelerator drain, W		.24
Cathode power		
Vaporizer, W	6	
Heater	0	
Keeper	<u>4.16</u>	
Total cathode power, W		10.16
Neutralizer power		
Vaporizer, W	1.42	
Heater, W	0	
Keeper, W	<u>6.55</u>	
Total neutralizer power, W		<u>7.97</u>
Total input power, W		52.07

Power efficiency, percent	48.0
Propellant utilization efficiency	
Discharge chamber only, percent	71.5
Including neutralizer, percent	67.3
Overall efficiency, percent	32.3
Discharge losses	
Chamber only, EV/ion	348
Including keeper, EV/ion	515
Specific impulse, sec	2120
Thrust, mlb	0.36

**TABLE II. - PERFORMANCE PROFILE**  
**[2023 Hours]**

Beam power (corrected for thruster floating potential), W		25.0
Discharge power, W		9.39
Accelerator drain, W		.14
Cathode power		
Vaporizer, W	5.62	
Heater, W	0	
Keeper, W	<u>4.06</u>	
Total cathode power, W		9.68
Neutralizer power		
Vaporizer, W	1.07	
Heater, W	2.35	
Keeper, W	<u>8.20</u>	
Total neutralizer power, W		<u>11.62</u>
Total input power, W		55.83

Power efficiency, percent	44.9
Propellant utilization efficiency	
Discharge chamber only, percent	74.5
Including neutralizer, percent	69.6
Overall efficiency, percent	31.3
Discharge losses	
Chamber only, EV/ion	376
Including keeper, EV/ion	538
Specific impulse, sec	2200
Thrust, mlb	0.36

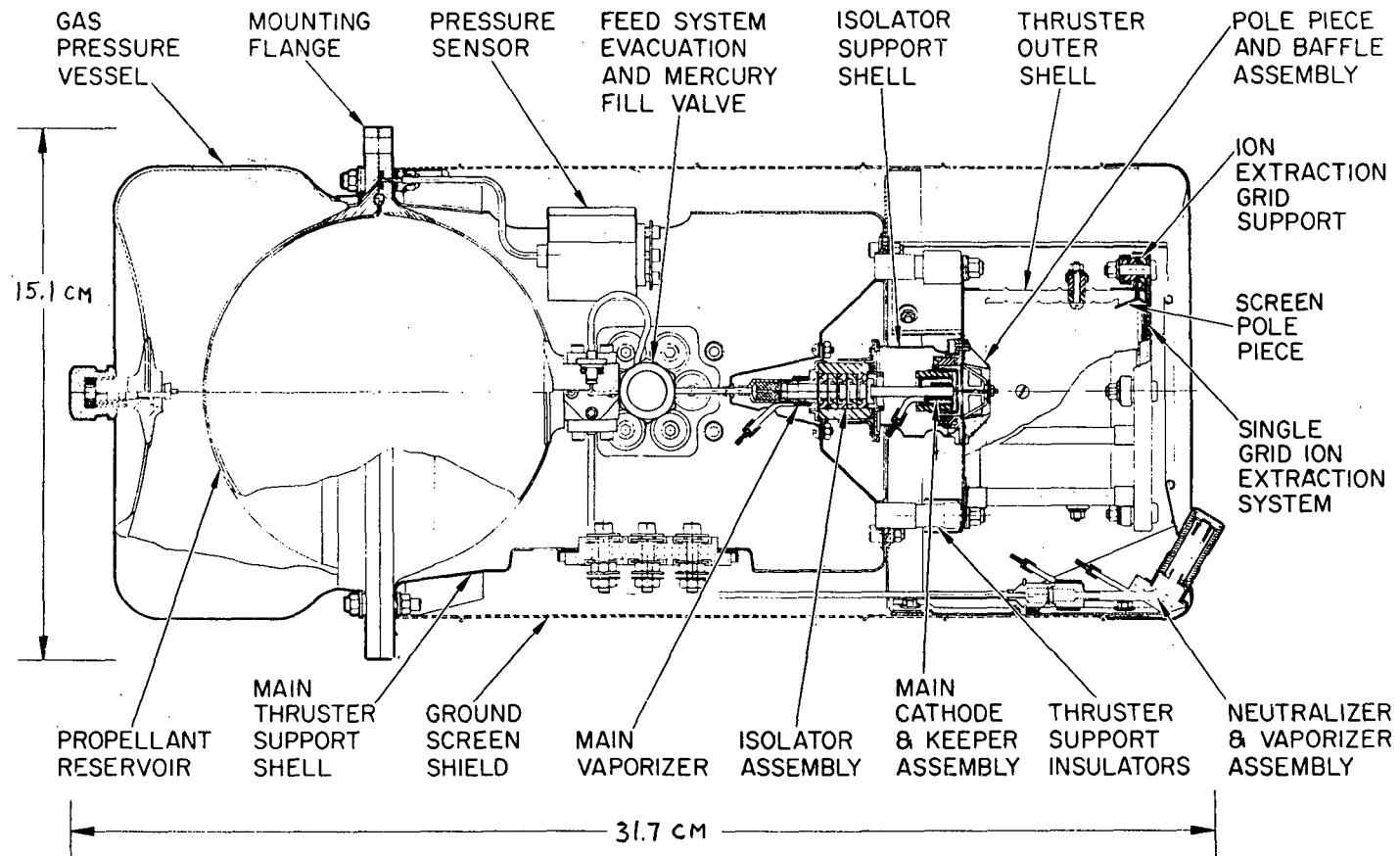


Figure 1. - Section view of the SIT-5 system.

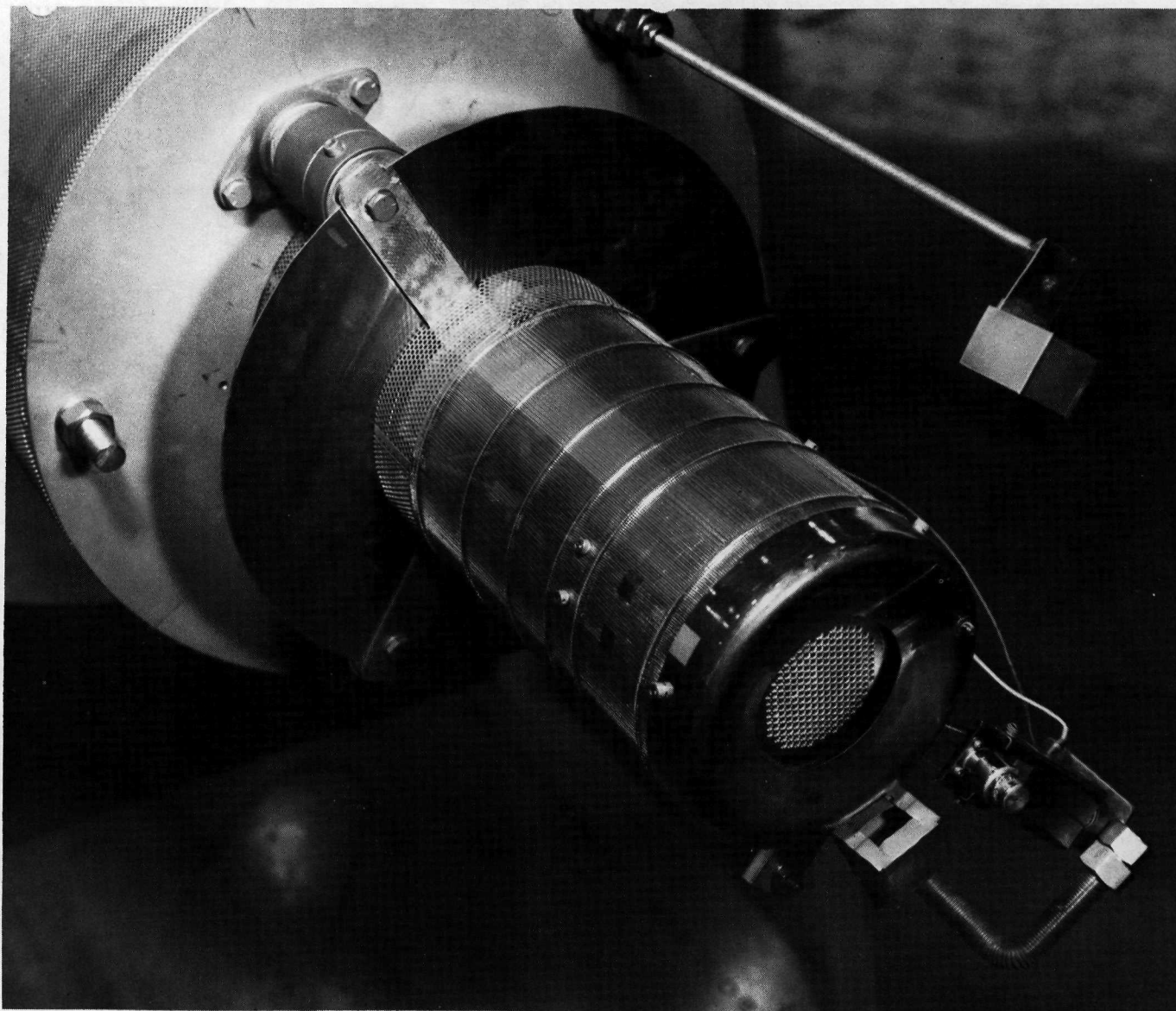


Figure 2. - Test installation of modified SIT-5 thruster.

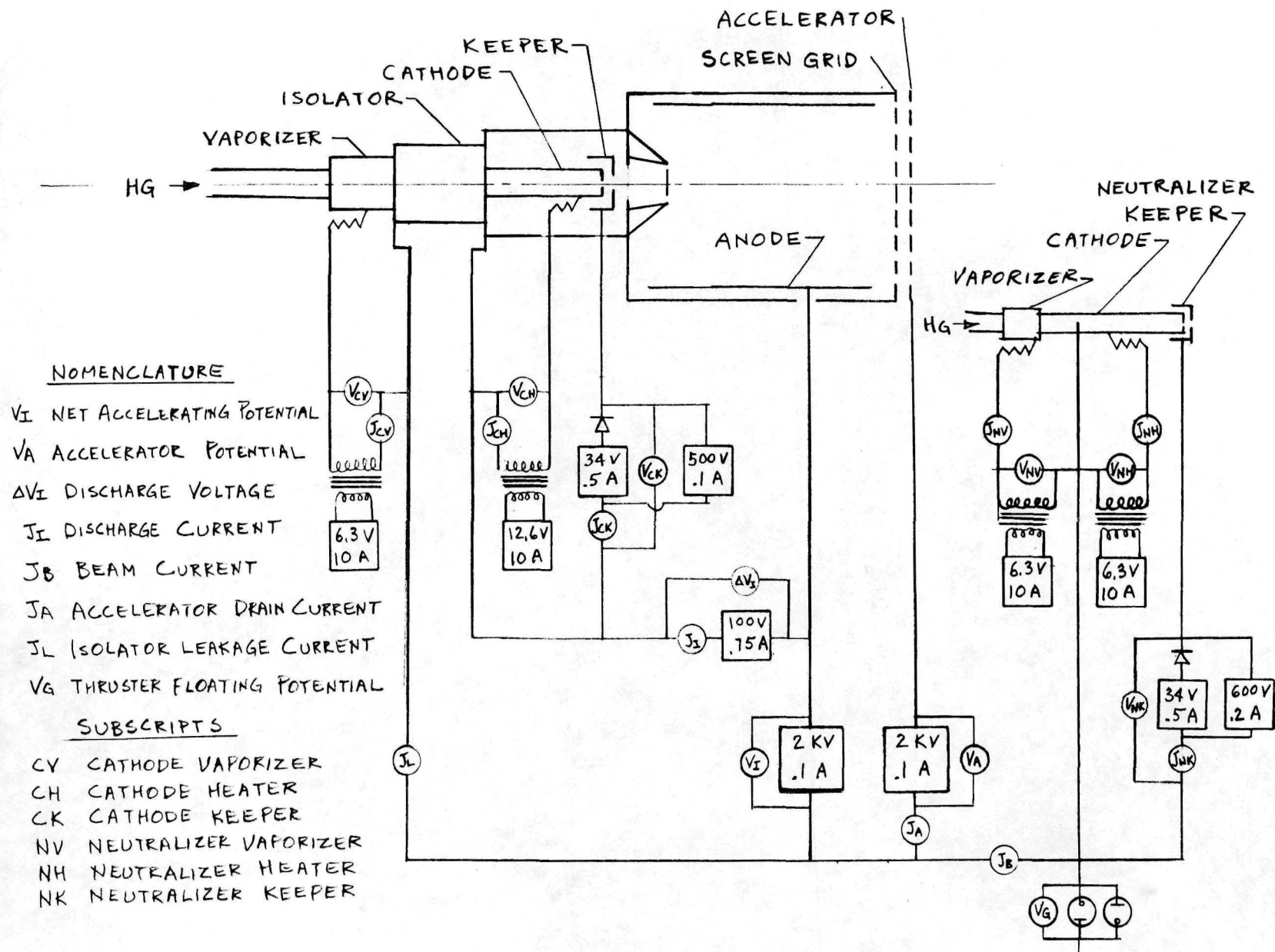


Figure 3. - Electrical schematic of power and data system.

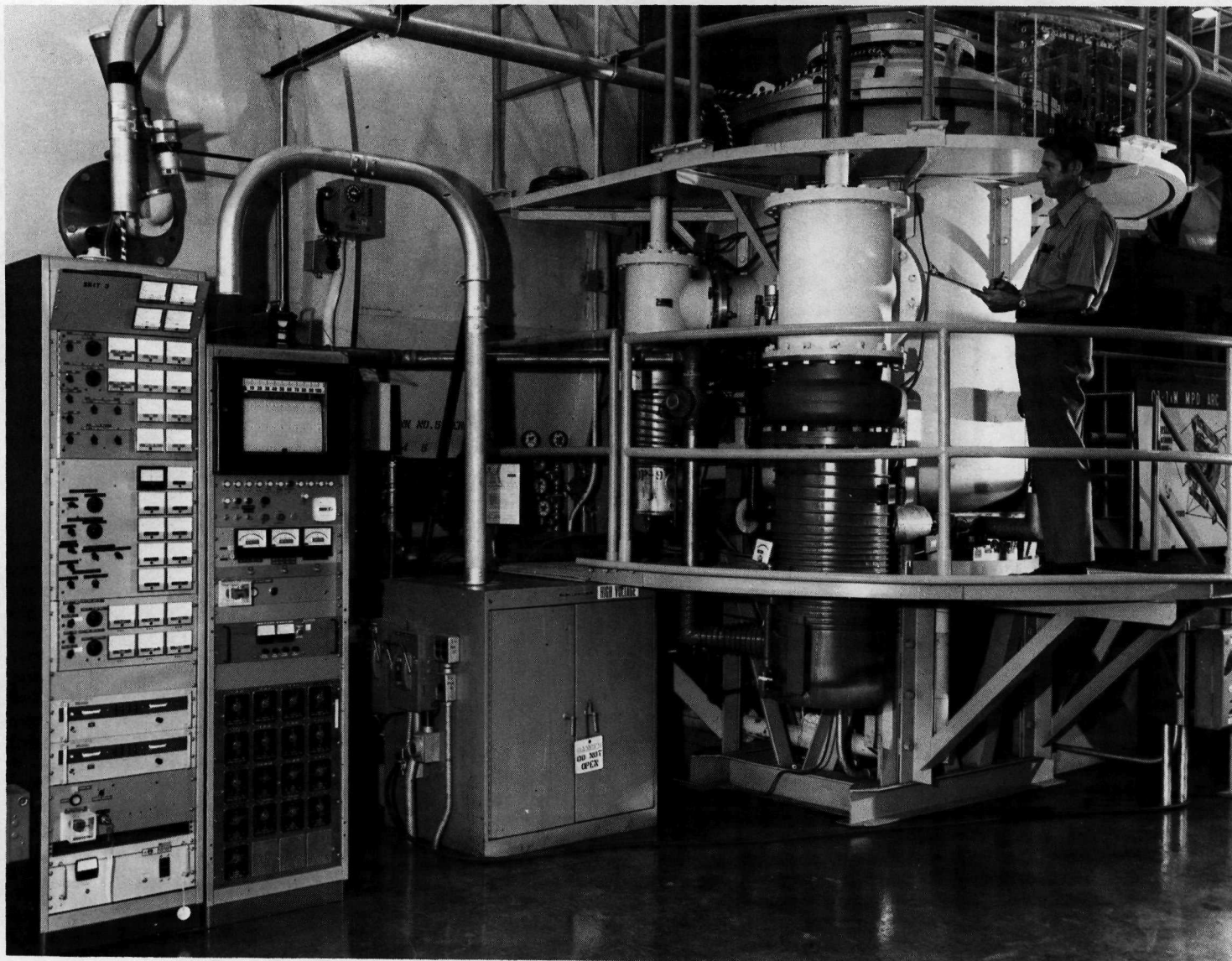


Figure 4. - Photograph of test facility.

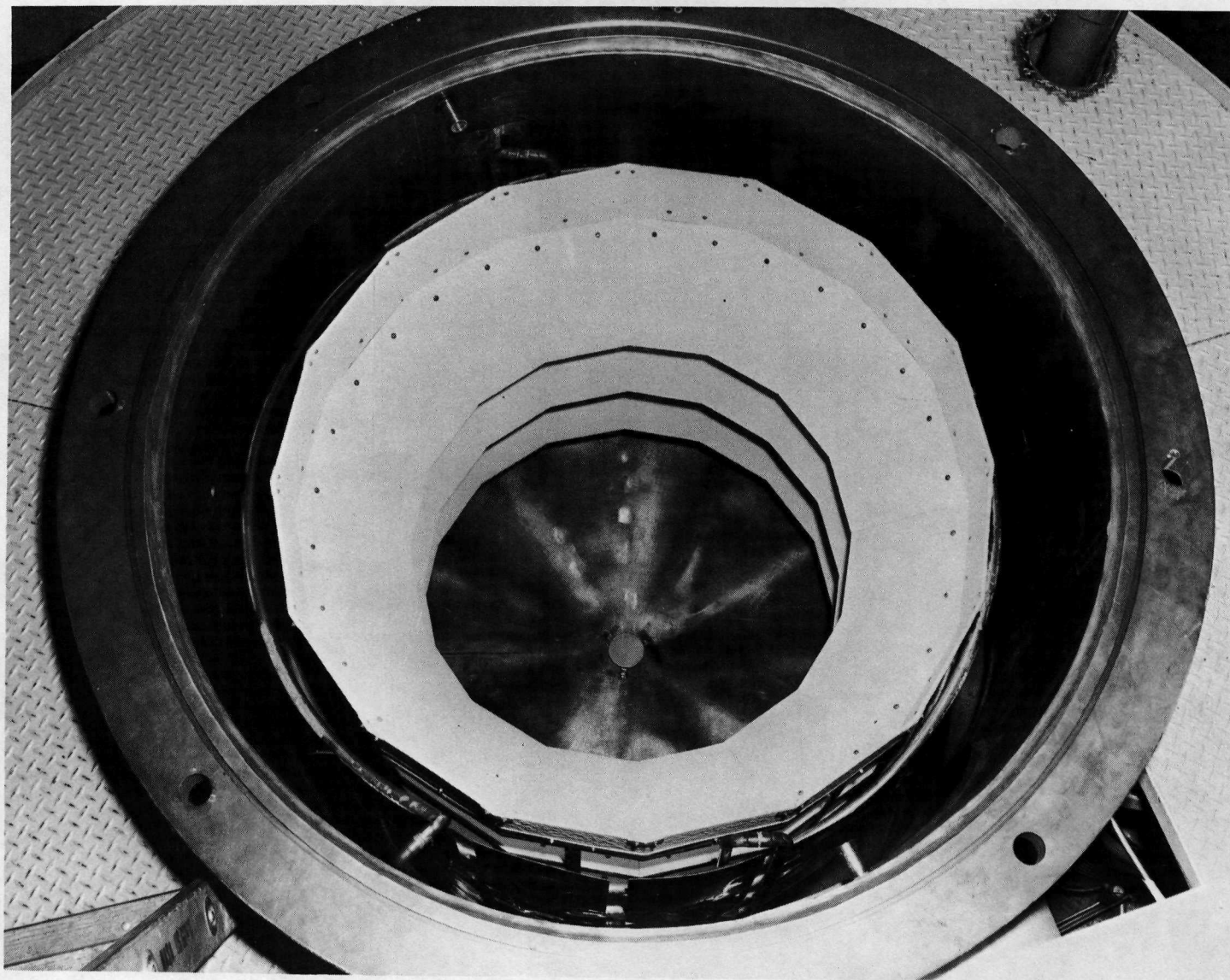


Figure 5. - Photograph of tank interior before test.

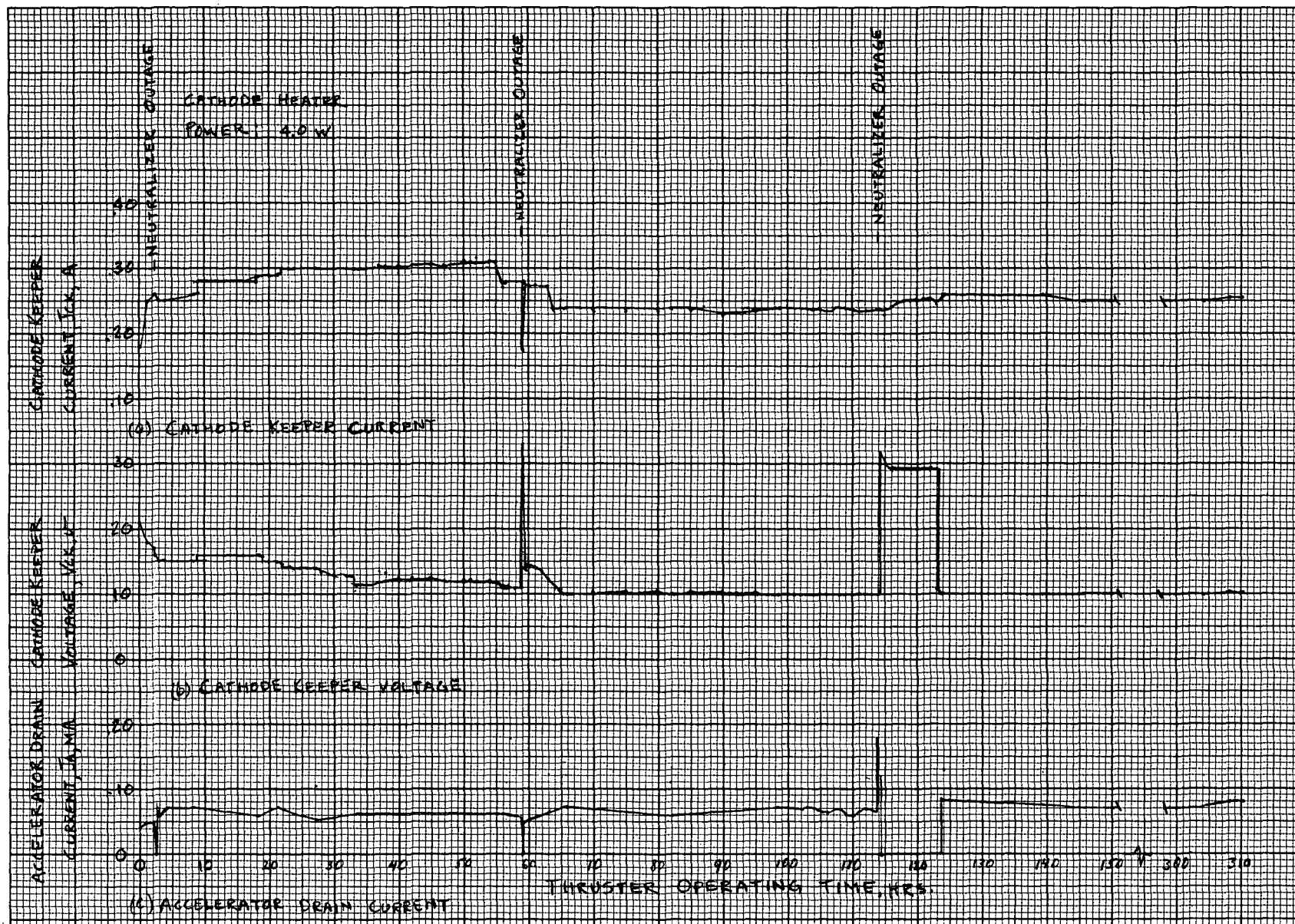


Figure 6. - Abridged time history of durability test showing thruster variables.

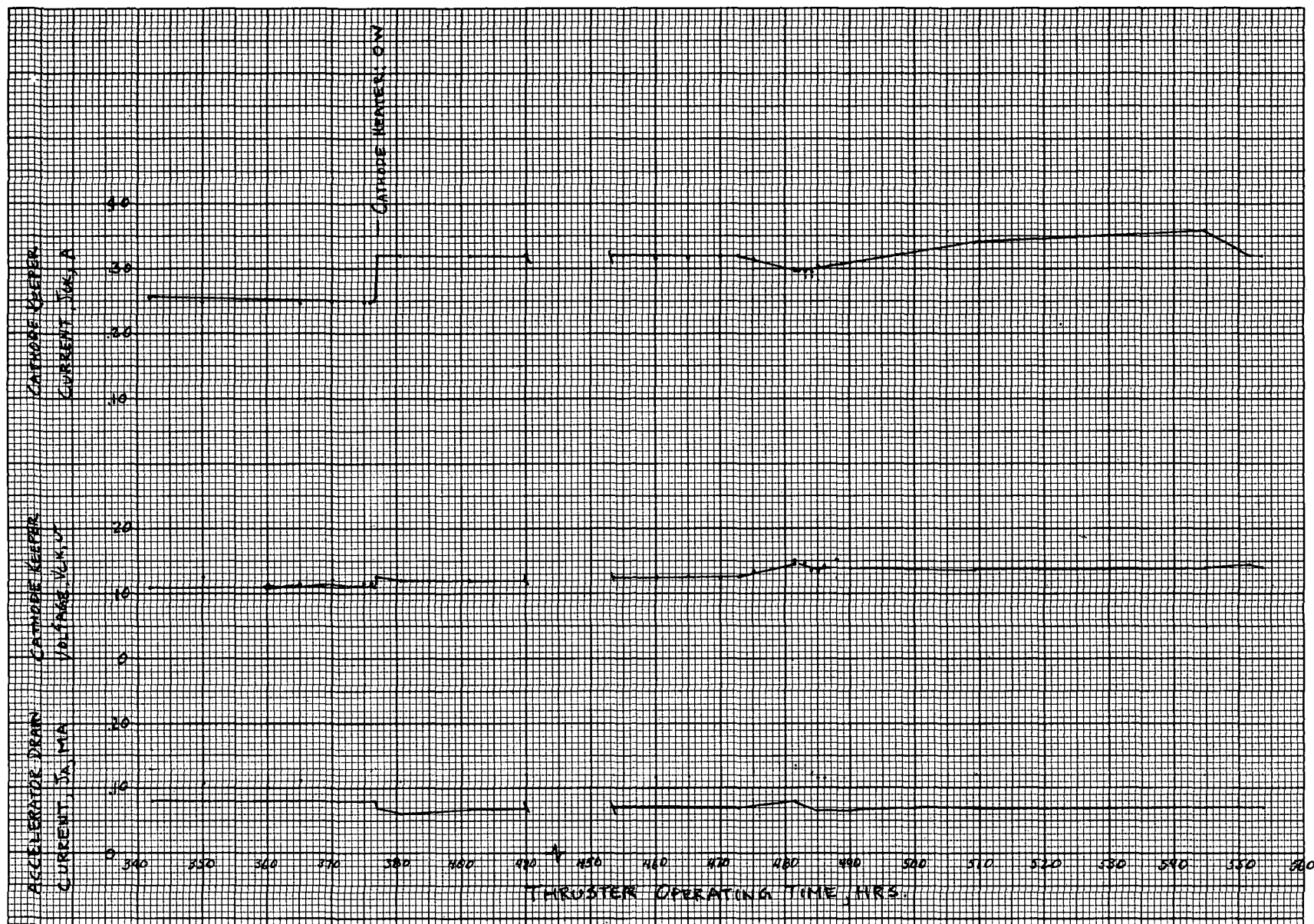


Figure 6. - Continued.

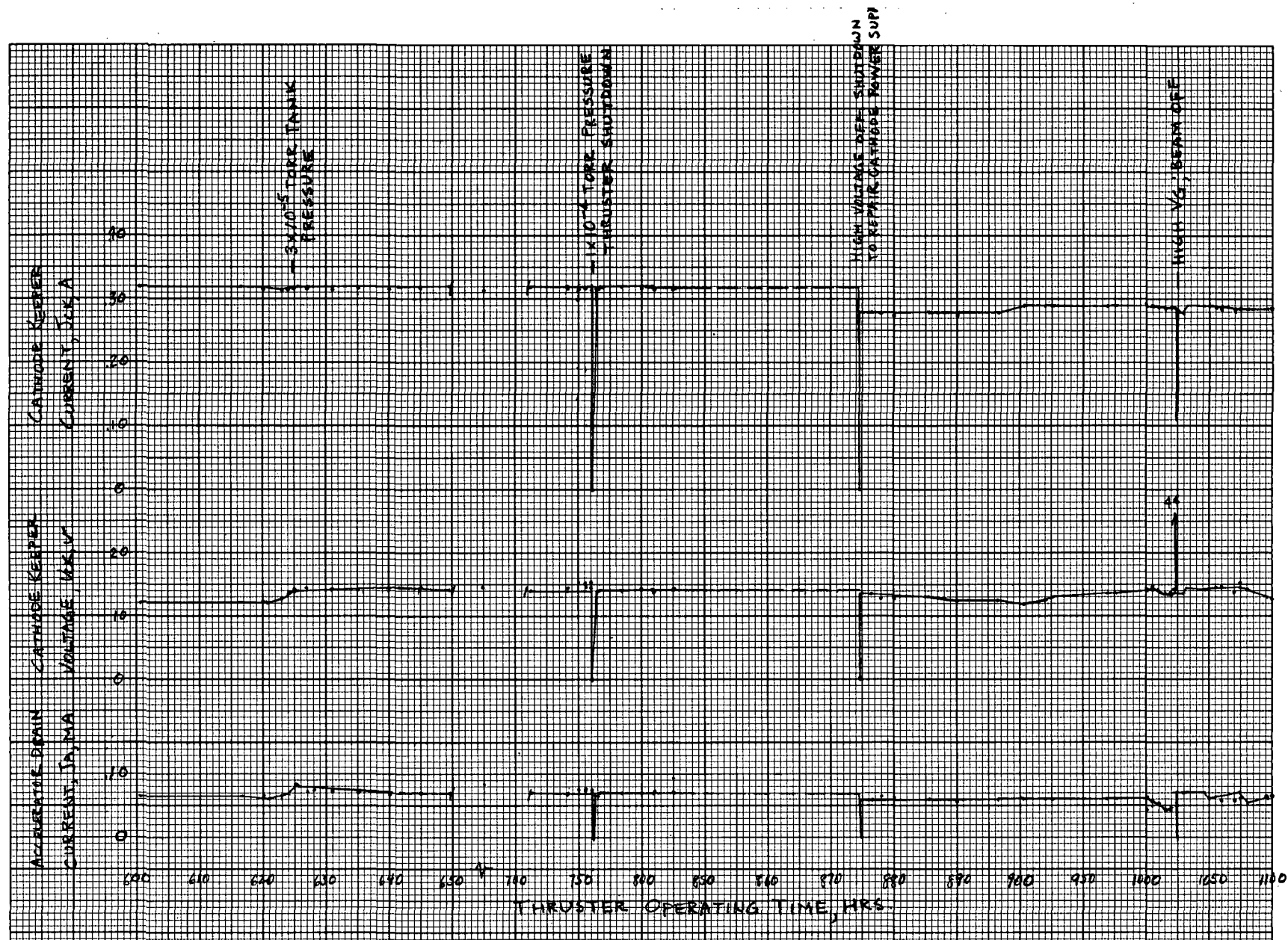


Figure 6. - Continued.

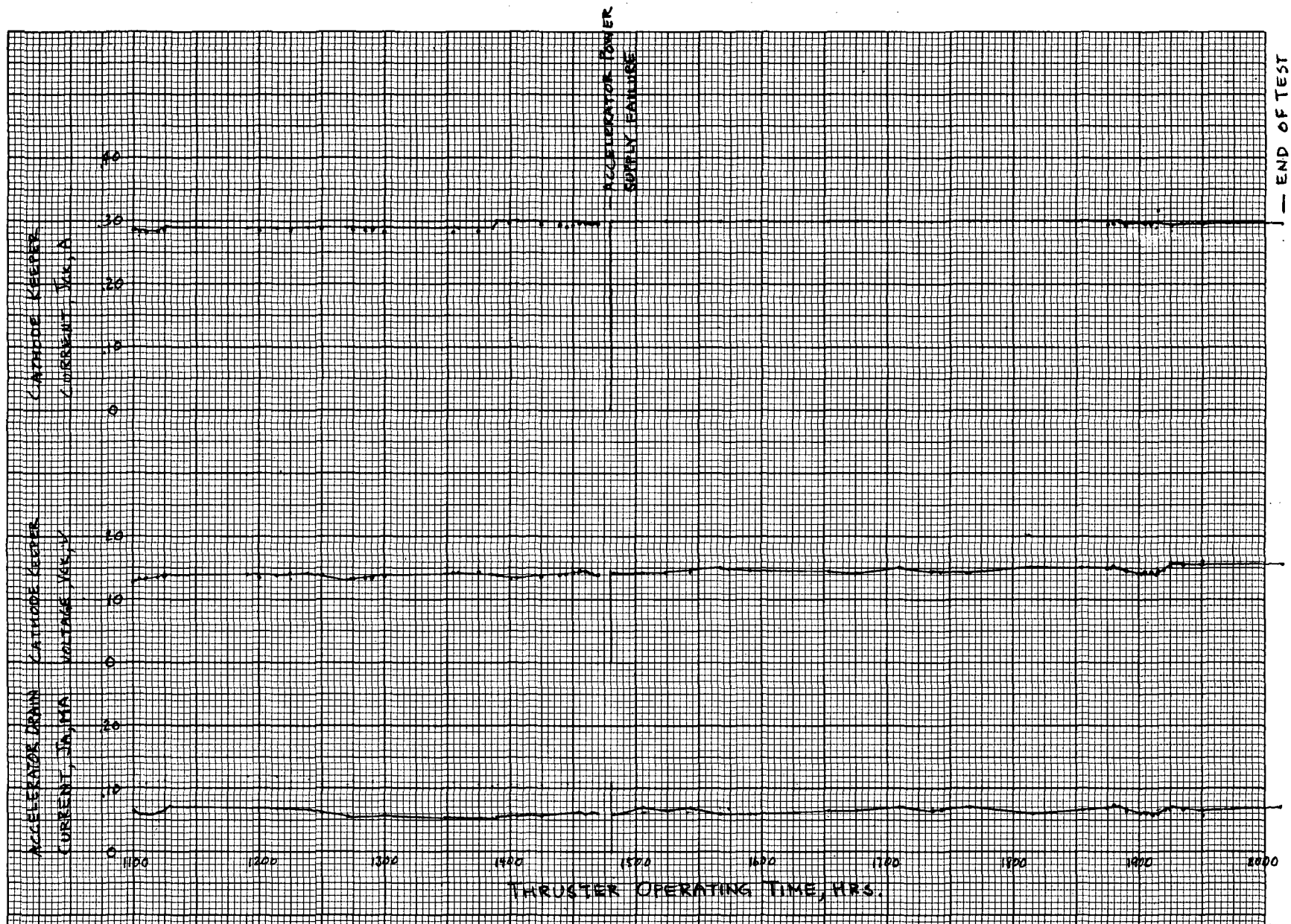


Figure 6. - Concluded.

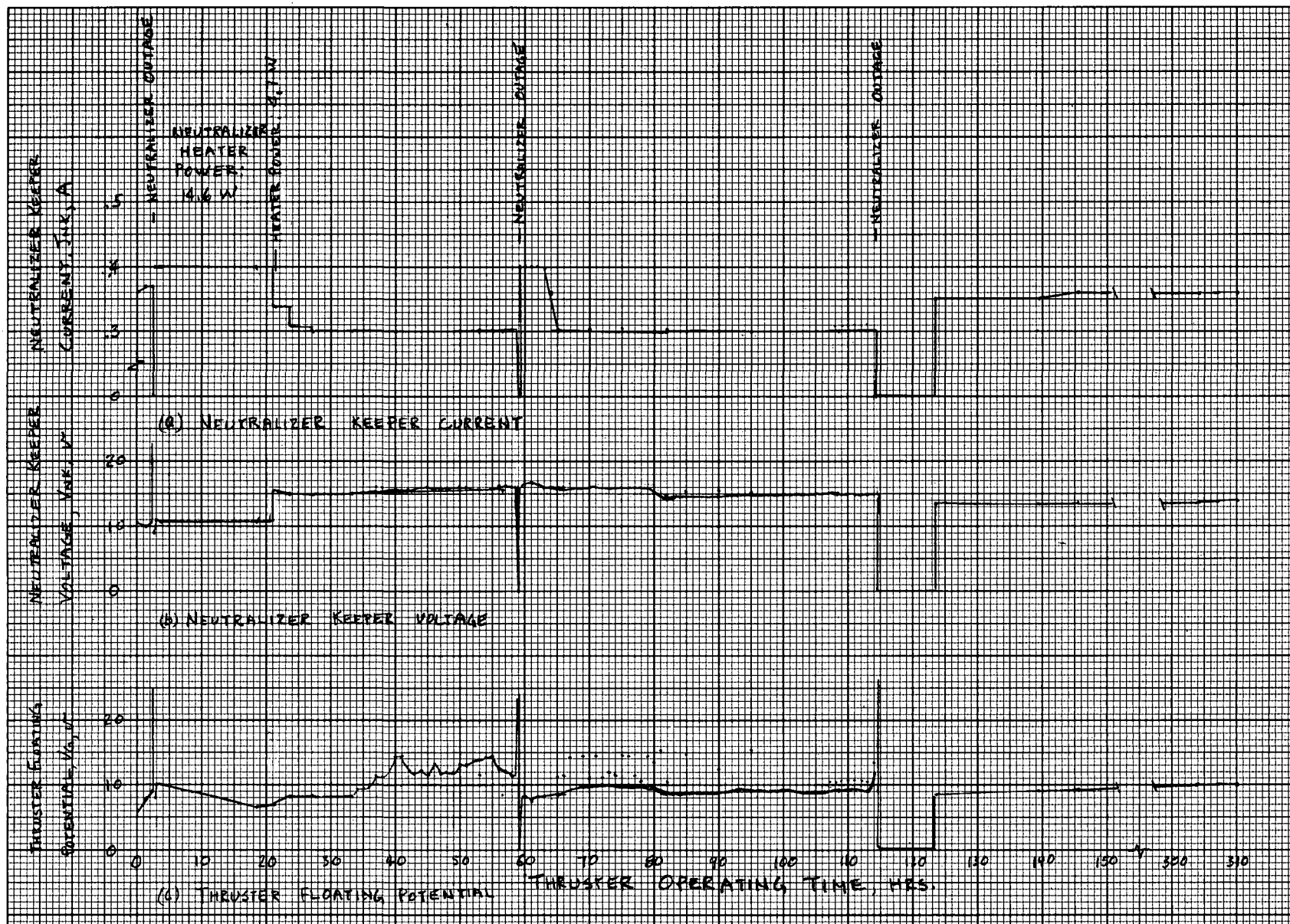


Figure 7. - Abridged time history of durability test showing neutralizer variables.

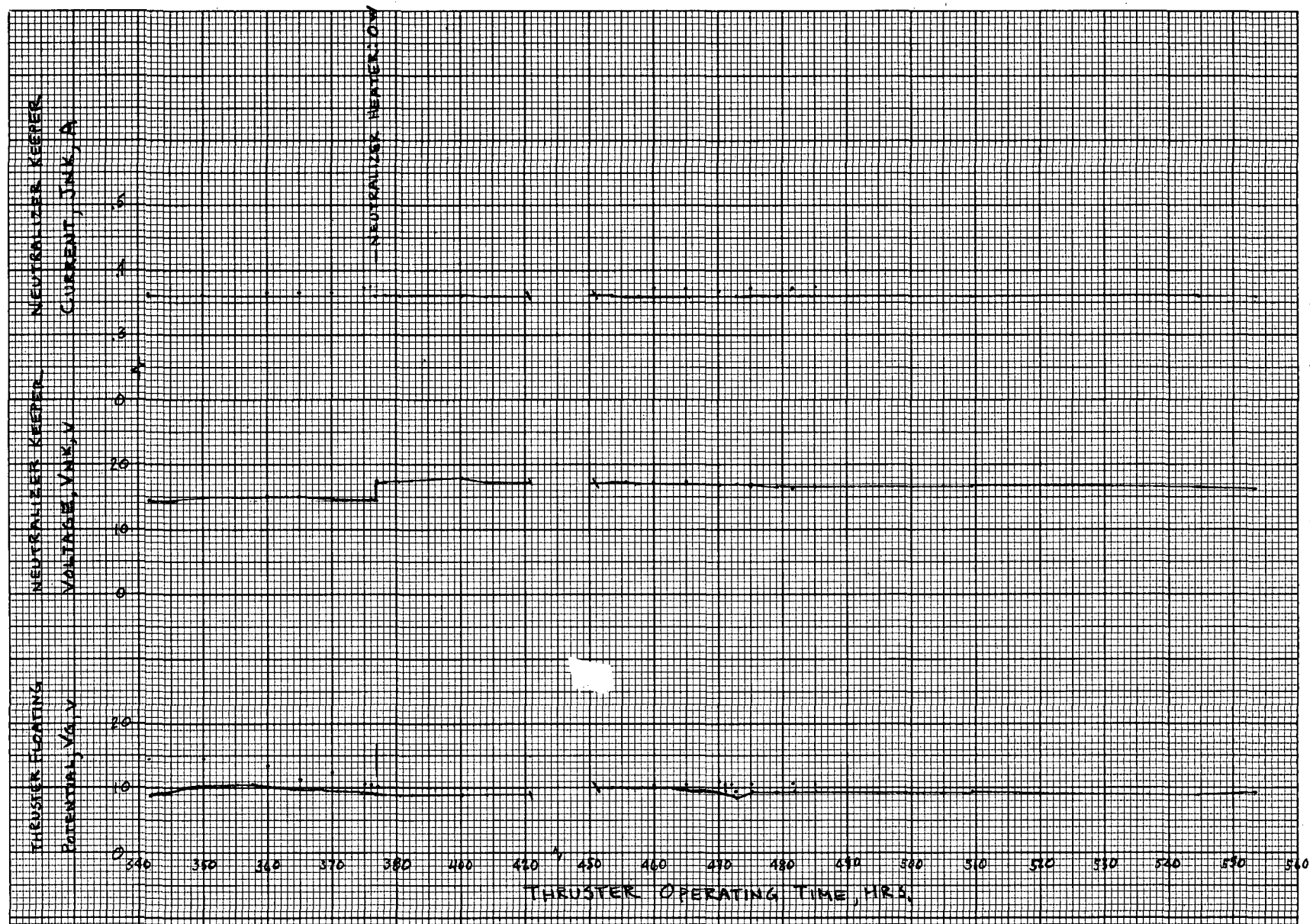


Figure 7. - Continued.

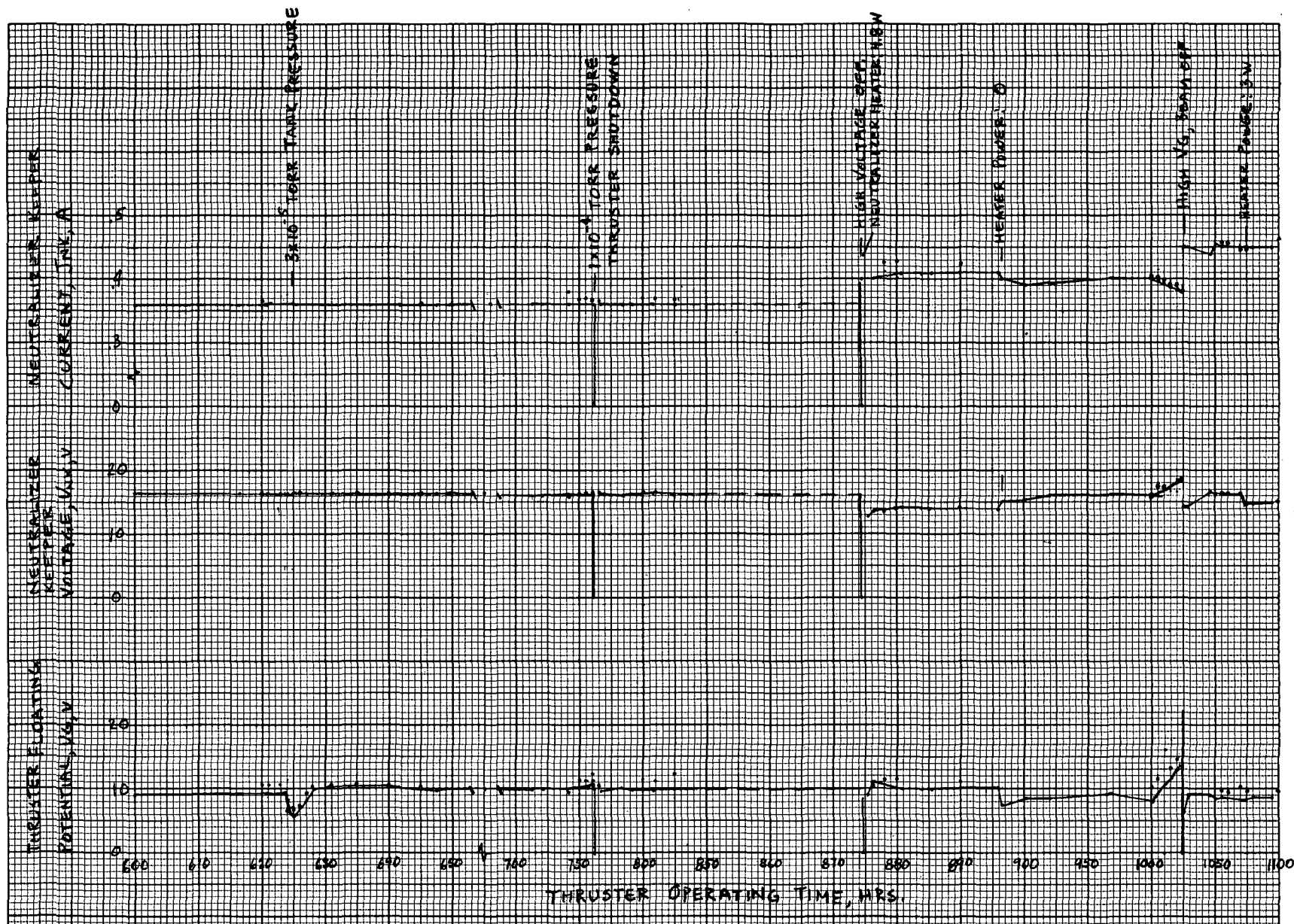


Figure 7. - Continued.

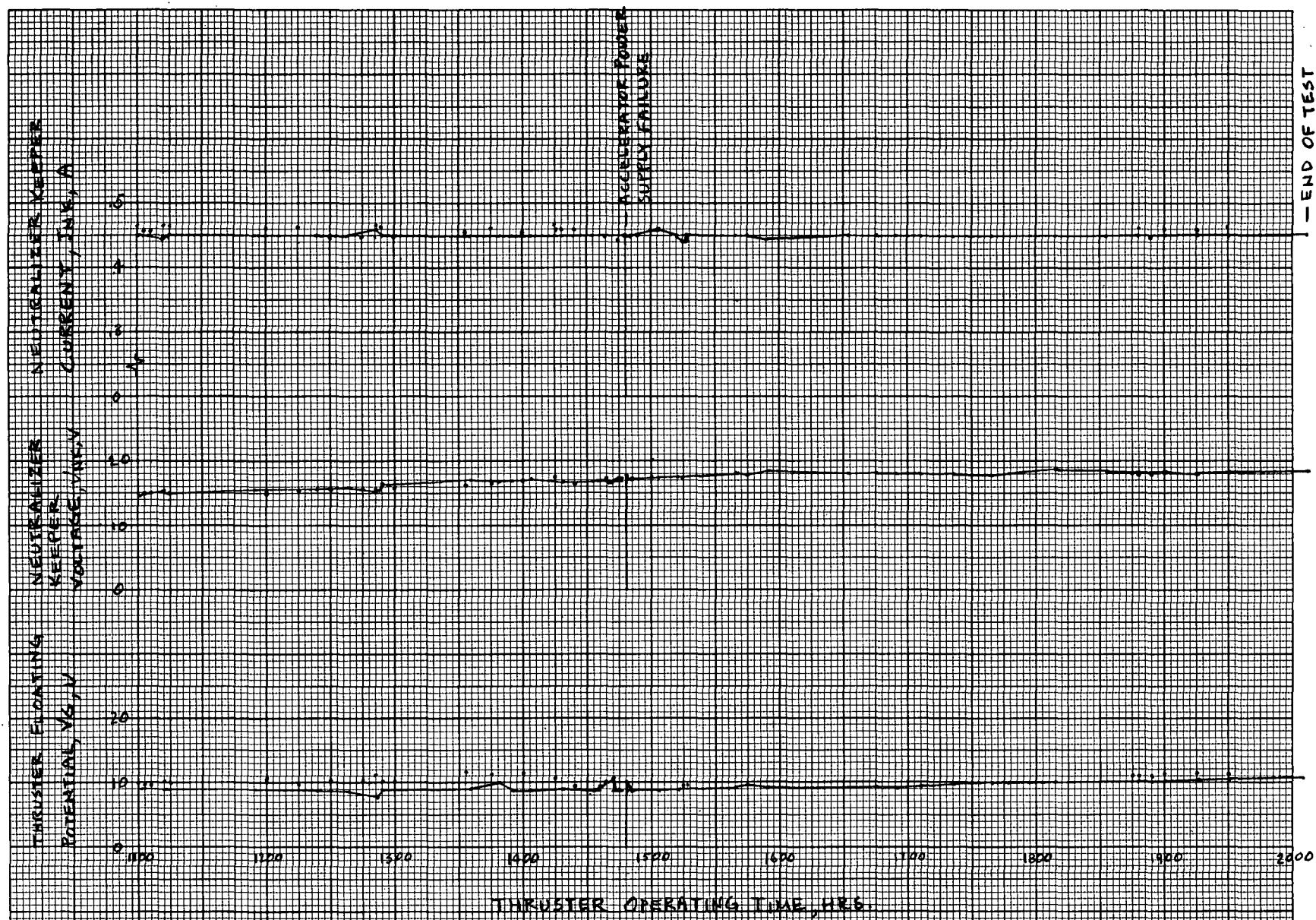


Figure 7. - Concluded.

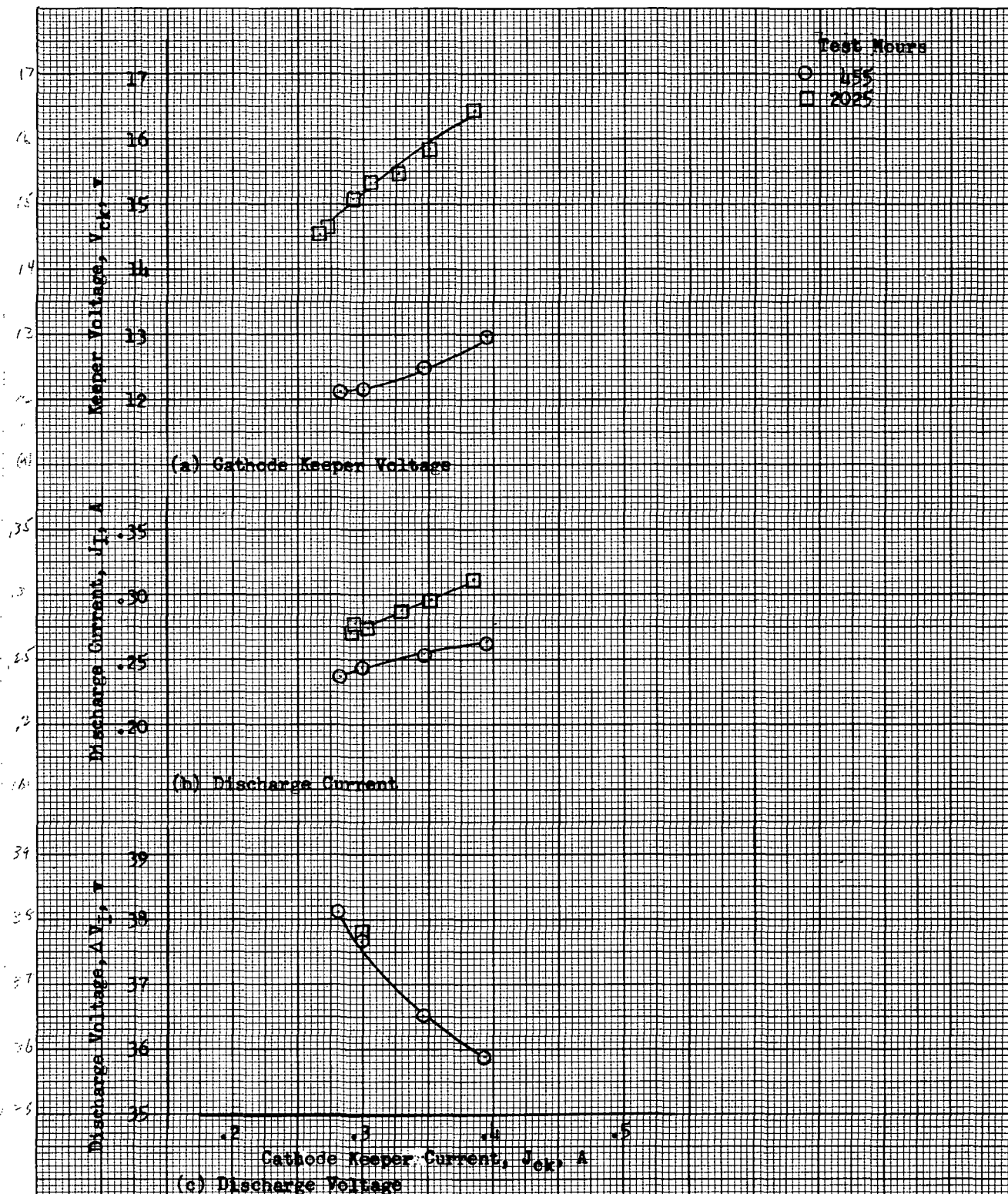


Figure 8.- Effects of varying cathode keeper current. Beam current, 25 mA; Cathode heater power, 0 W.

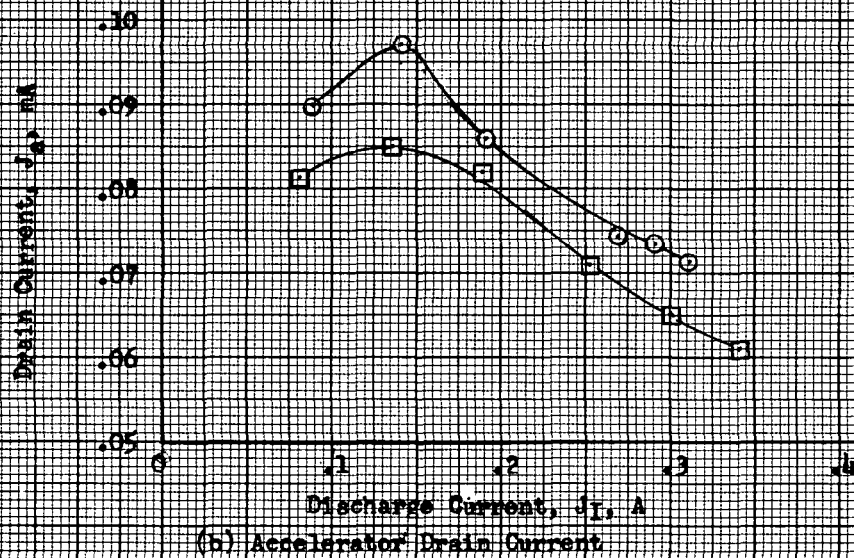


Figure 9.- Effects of varying discharge current. Cathode keeper current, 0.30 - 0.32 A; Cathode heater power, 0 w.

38

37

Discharge Voltage,  $V_D$ , v

Test Hours

○ 455

□ 2025

38

36

34

32

(c) Discharge Voltage

Thruster Floating Potential,  $V_G$ , v

12

10

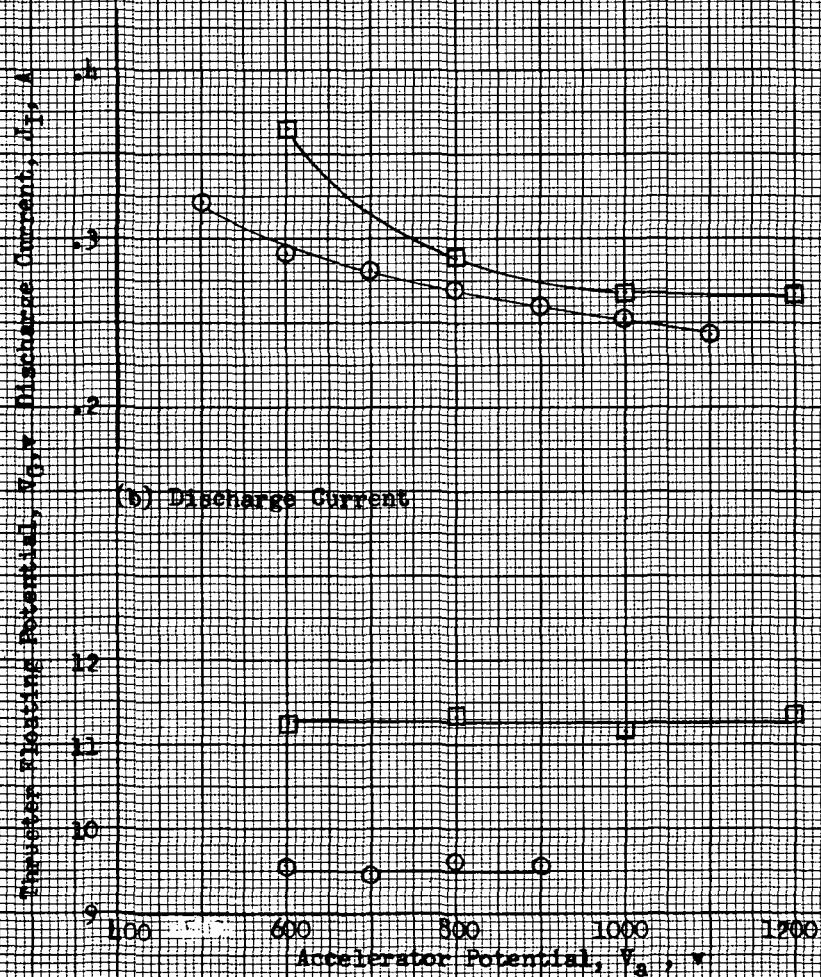
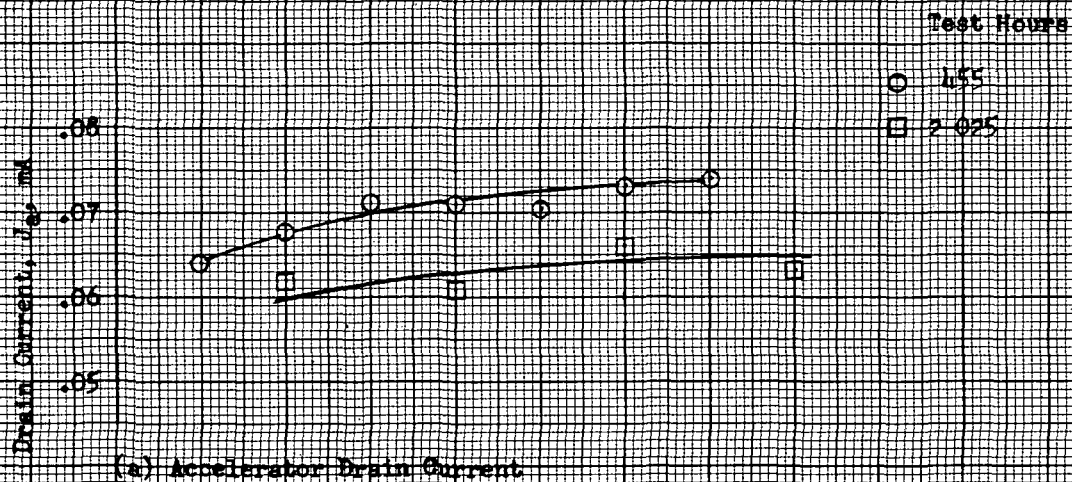
8

6

Discharge Current,  $J_I$ , A

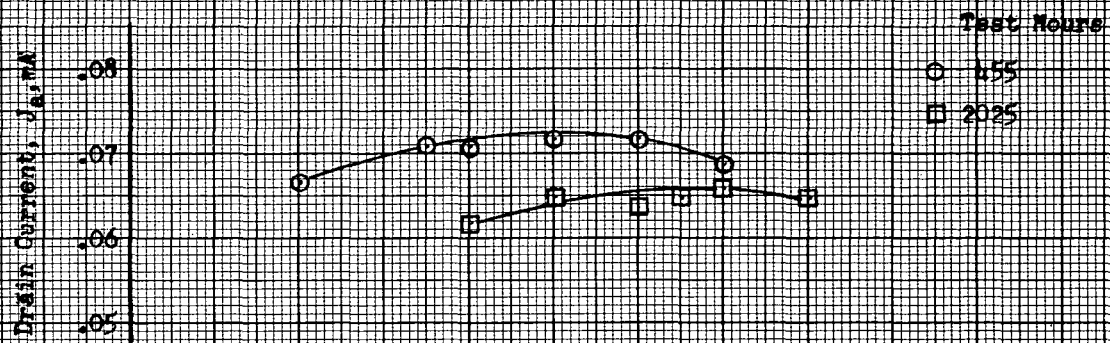
(d) Thruster Floating Potential

Figure 9.- Concluded

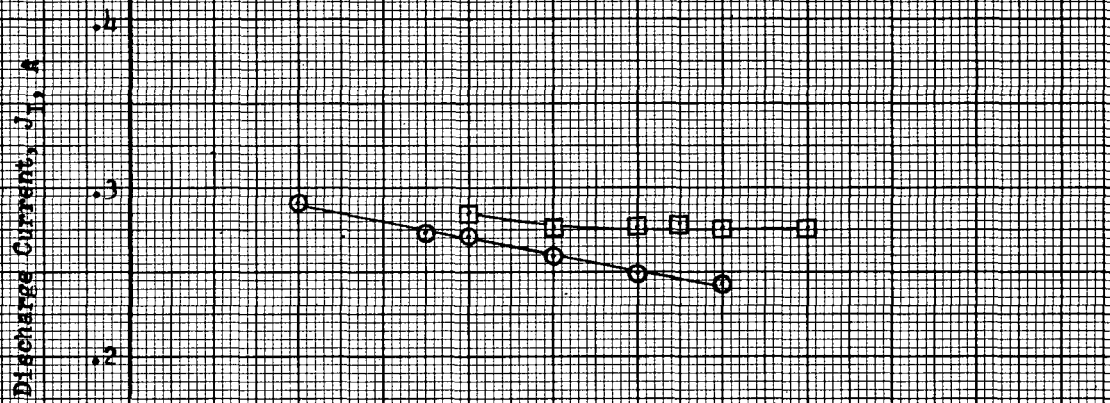


(a) Thruster Floating Potential

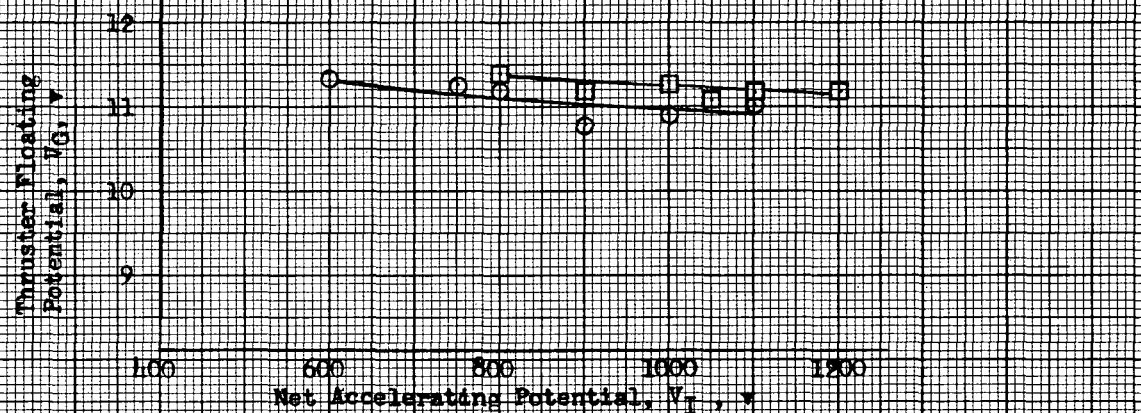
Figure 10.-Effects of varying accelerator potential, Beam current, 25 mA;  
Net accelerating potential, 1010 V.



(a) Accelerator Drain Current

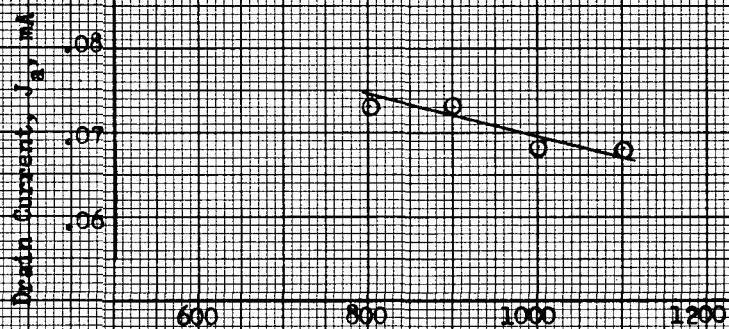


(b) Discharge Current

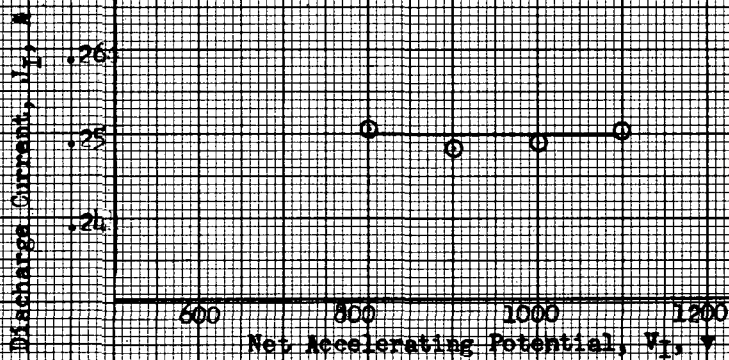


(c) Thruster Floating Potential

Figure 11.-Effects of varying net accelerating potential. Beam current, 25mA; Accelerator potential, -1000 v.

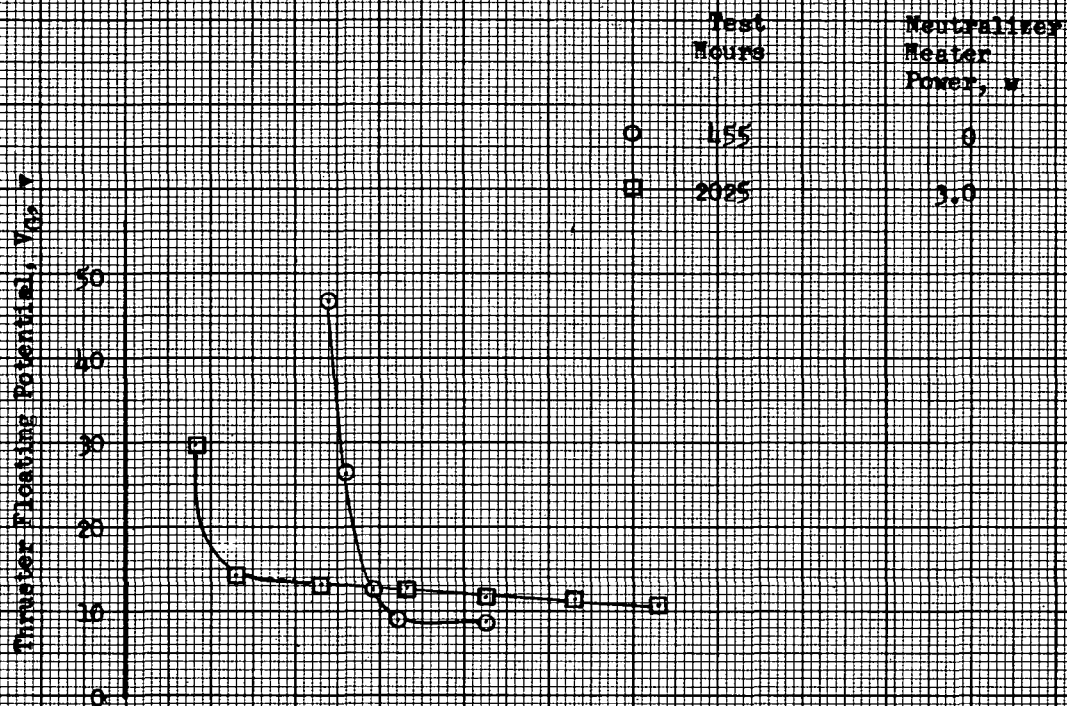


(a) Accelerator Drain Current

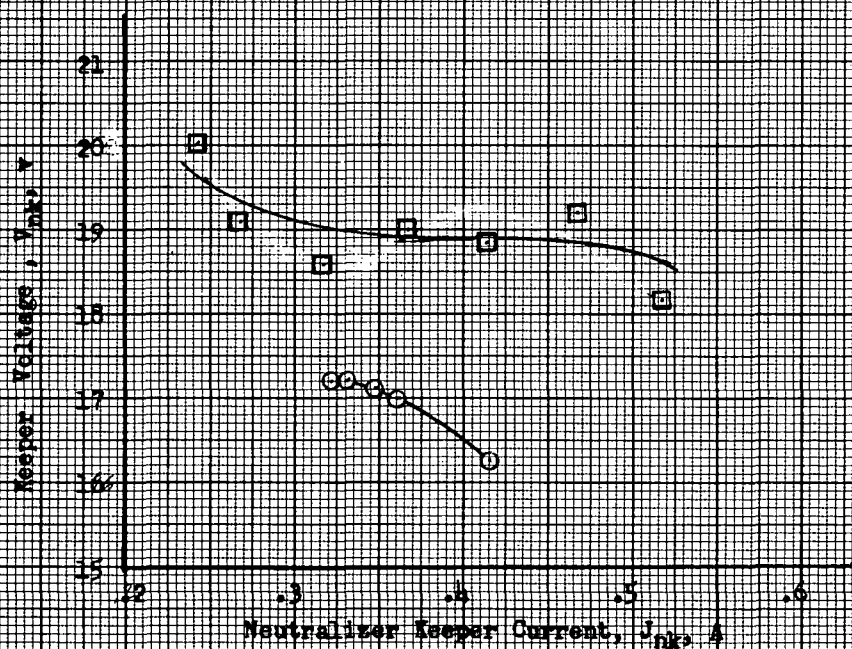


(b) Discharge Current

Figure 12.—Effects of varying net accelerating potential with total voltage,  $V_I + |V_a| = 2010$  v. Test hours, 455.



(a) Thruster Floating Potential



(b) Neutralizer Keeper Voltage

Figure 13.- Effects of varying neutralizer keeper current. Beam current, 25mA;  
Neutralizer flow rate, 2.3 nA equivalent.

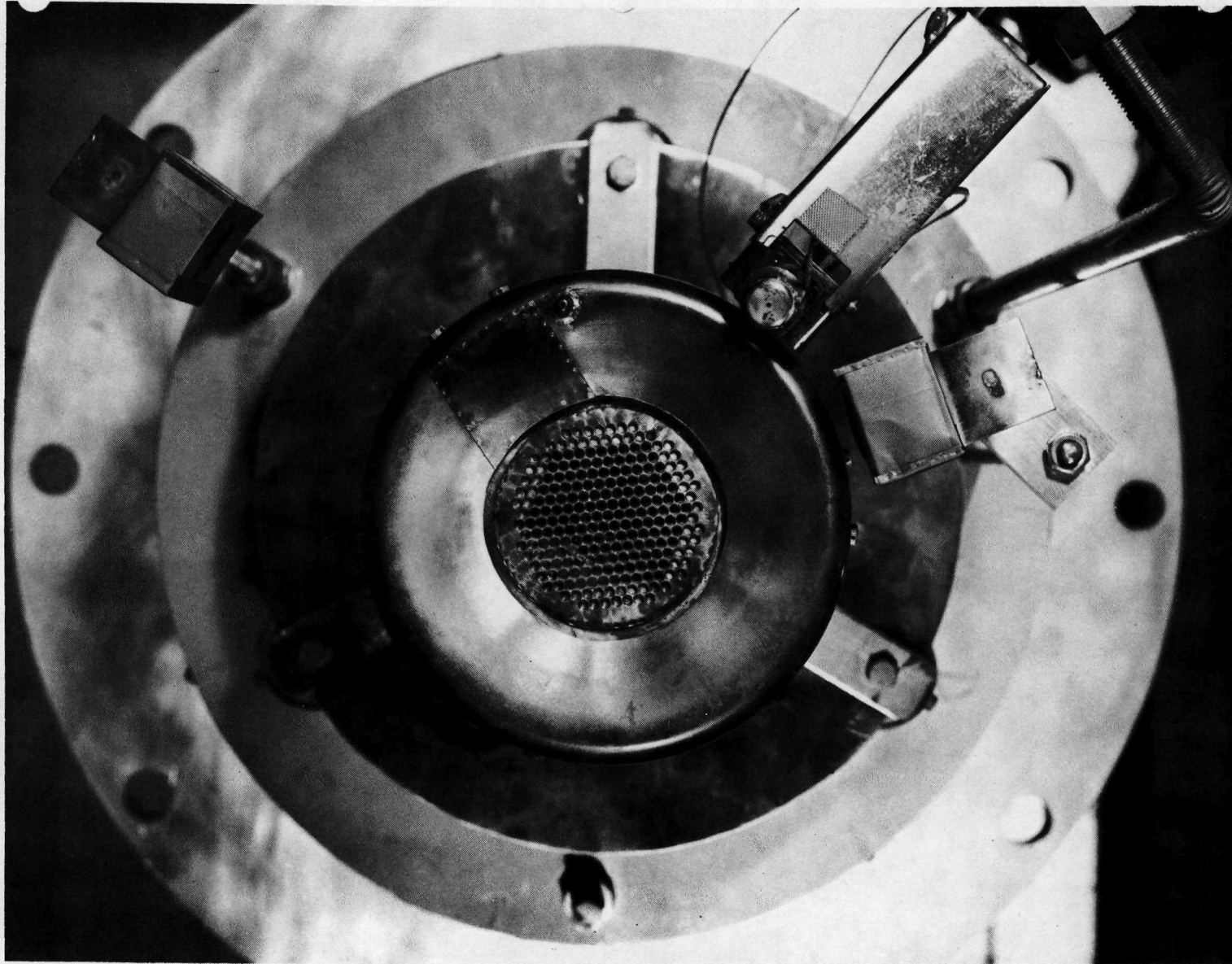


Figure 14. - Front view of accelerator grid after test.

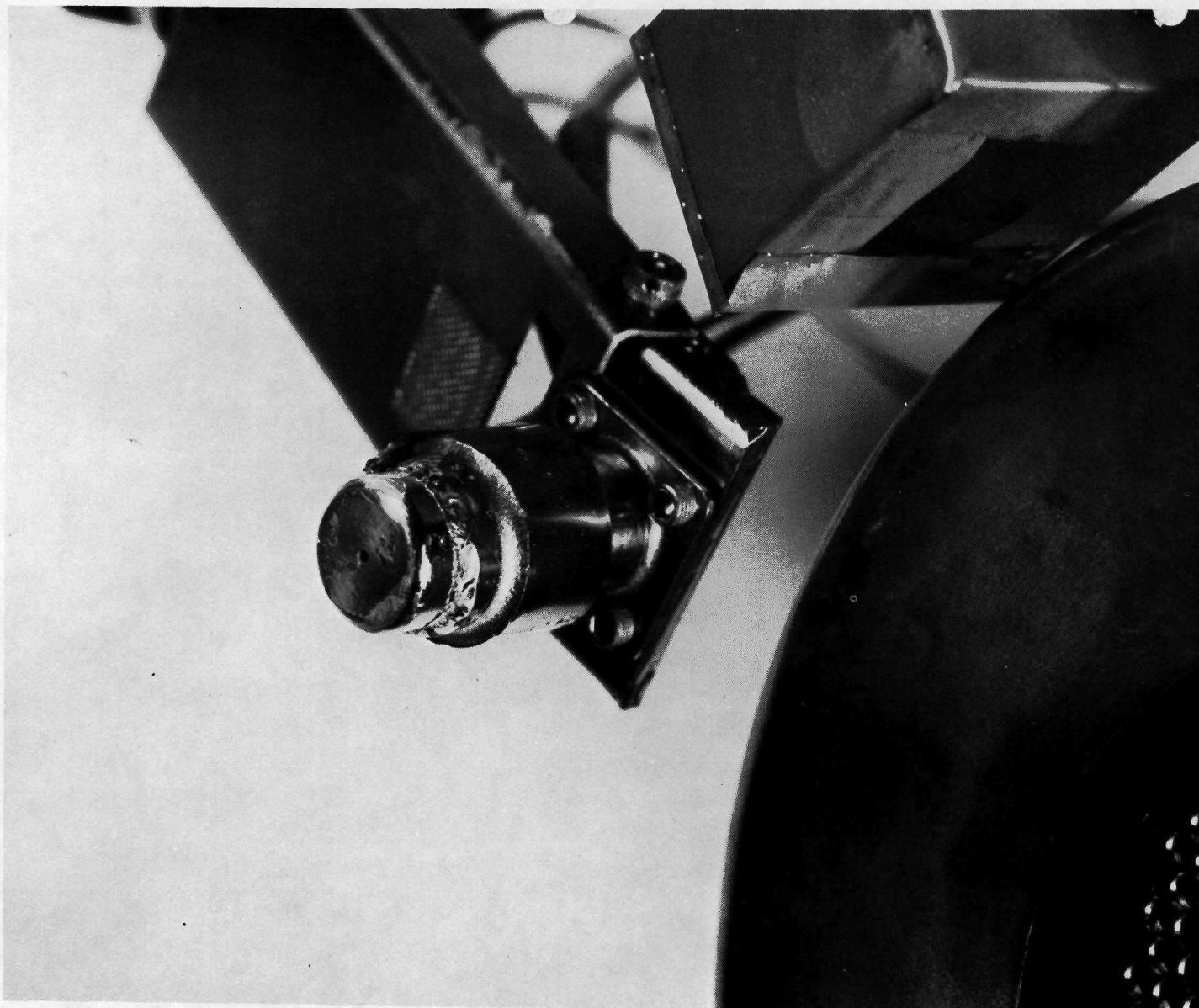


Figure 15. - Close-up view of neutralizer assembly after test.

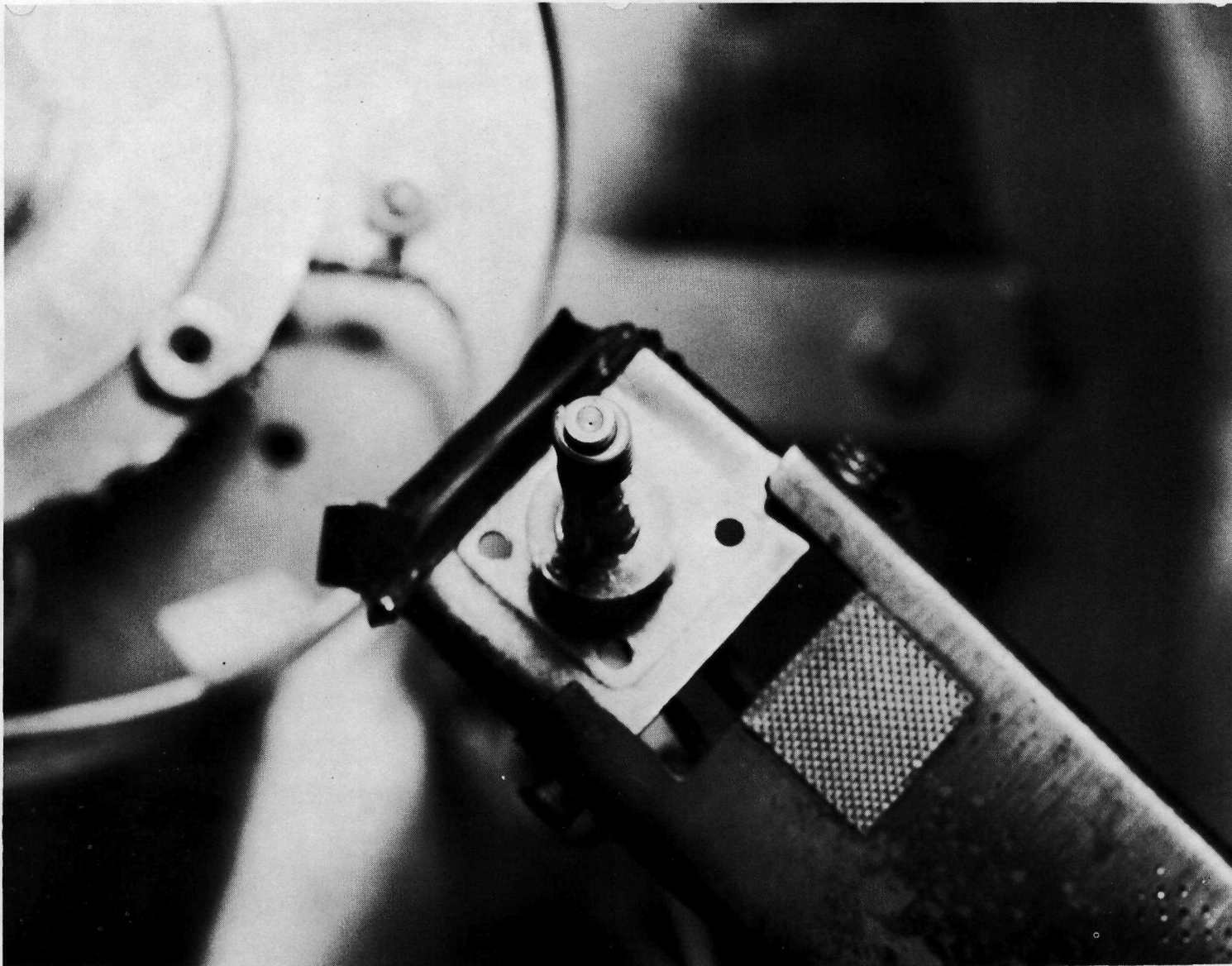
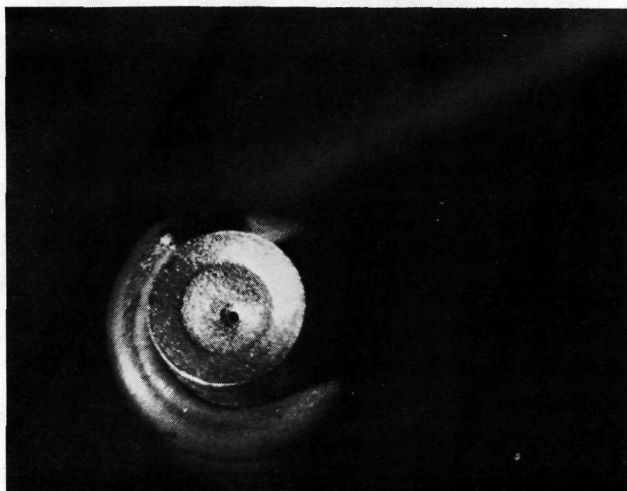
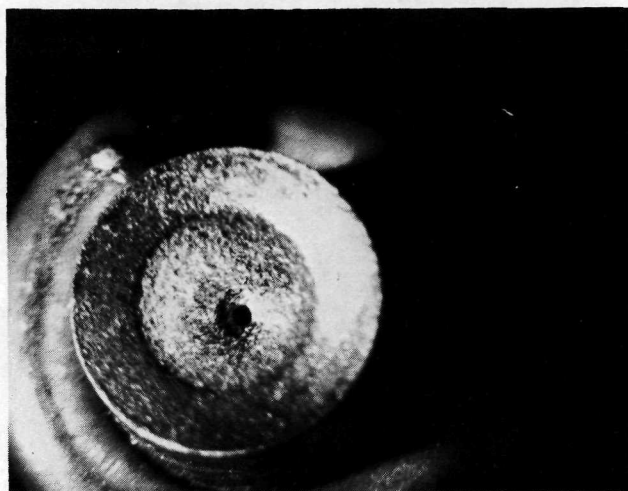


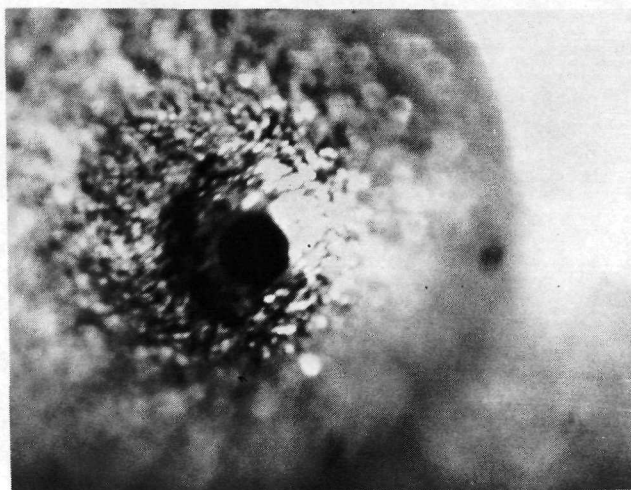
Figure 16. - Close-up photograph of neutralizer cathode tip after test.



(a) 7.5 X.



(b) 15 X.



(c) 52.5 X.

Figure 17. - Microphotographs of neutralizer cathode orifice after test.

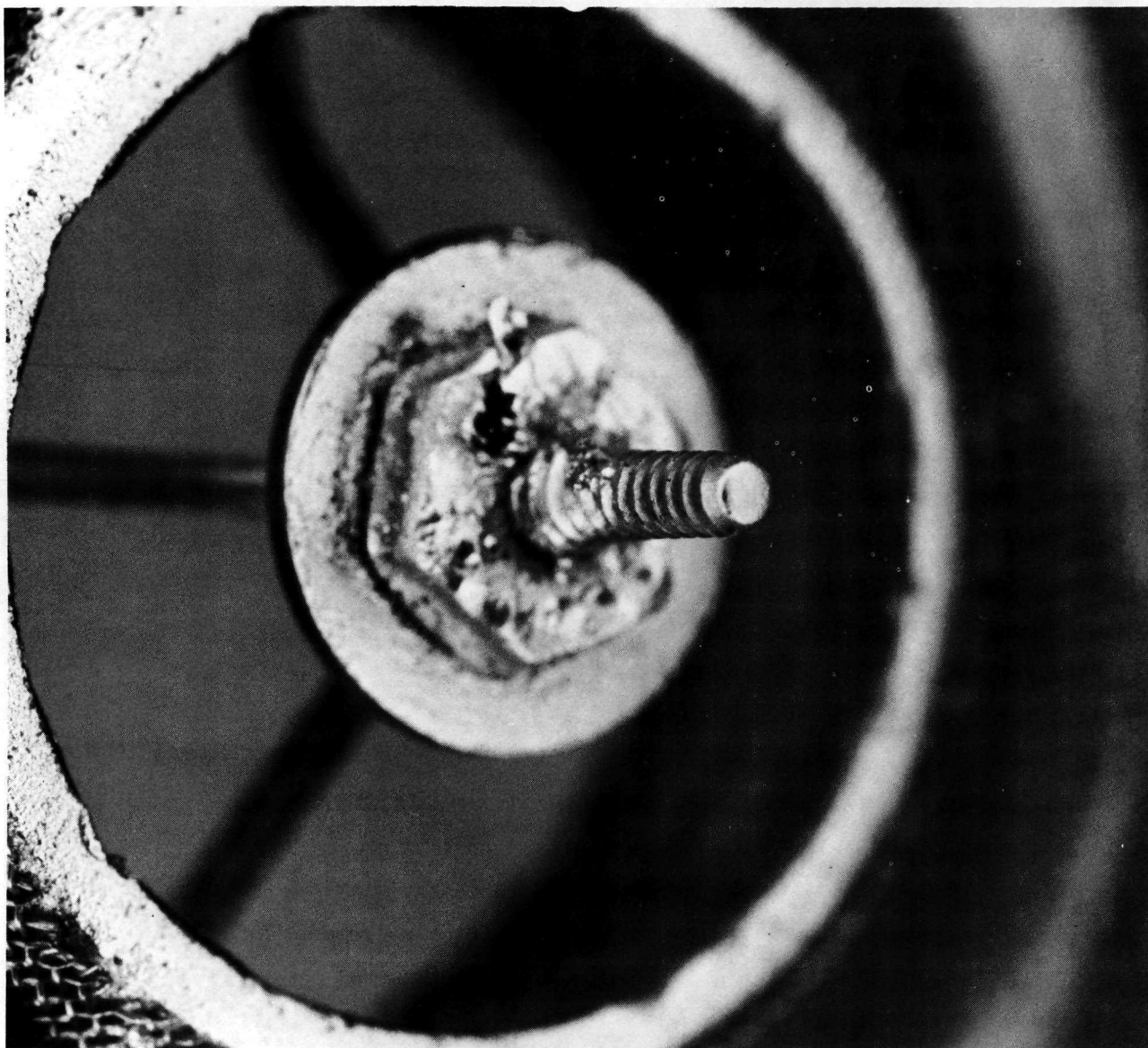


Figure 18. - Close-up photograph of pole piece baffle assembly.

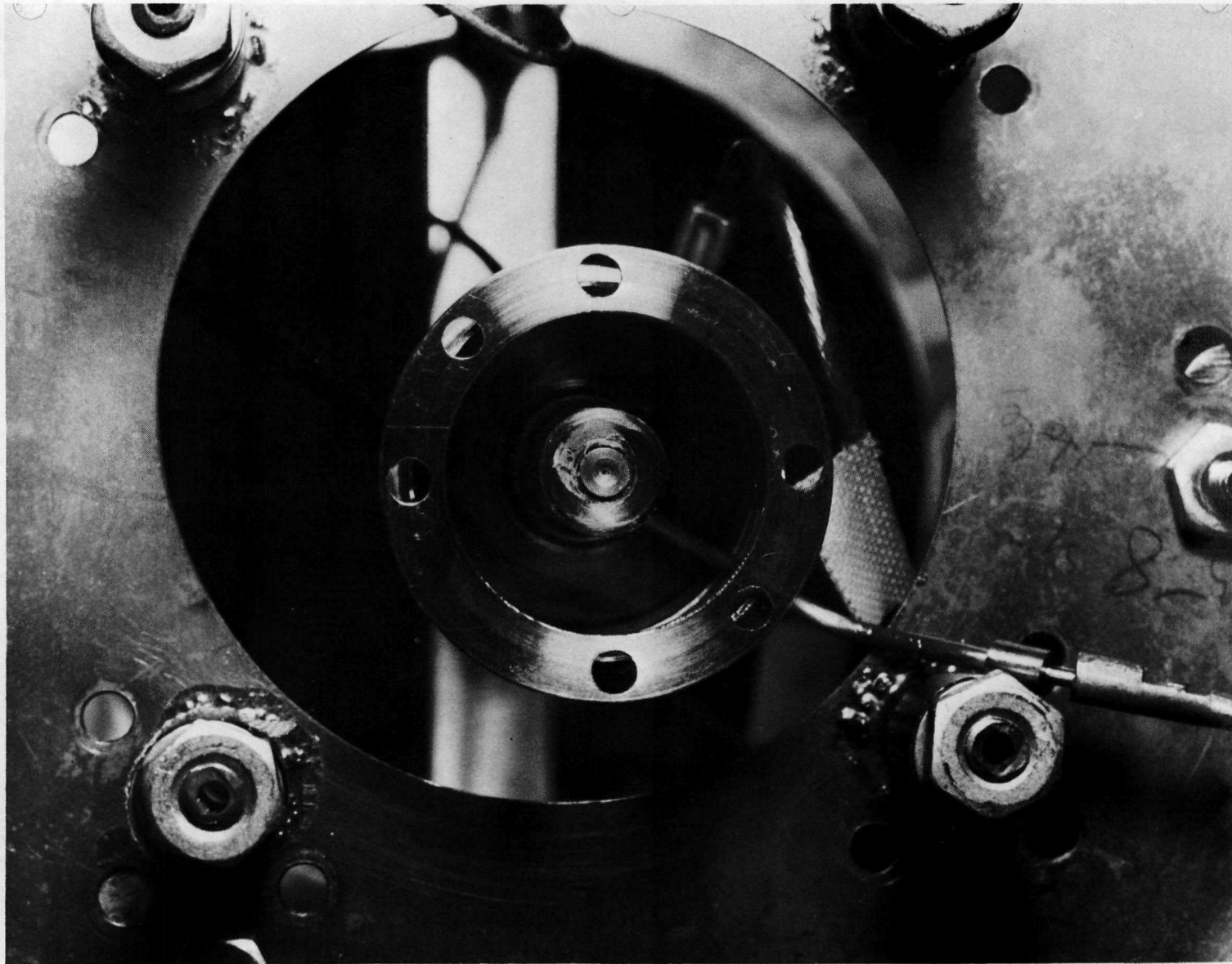


Figure 19. - Close-up photograph of main cathode tip.

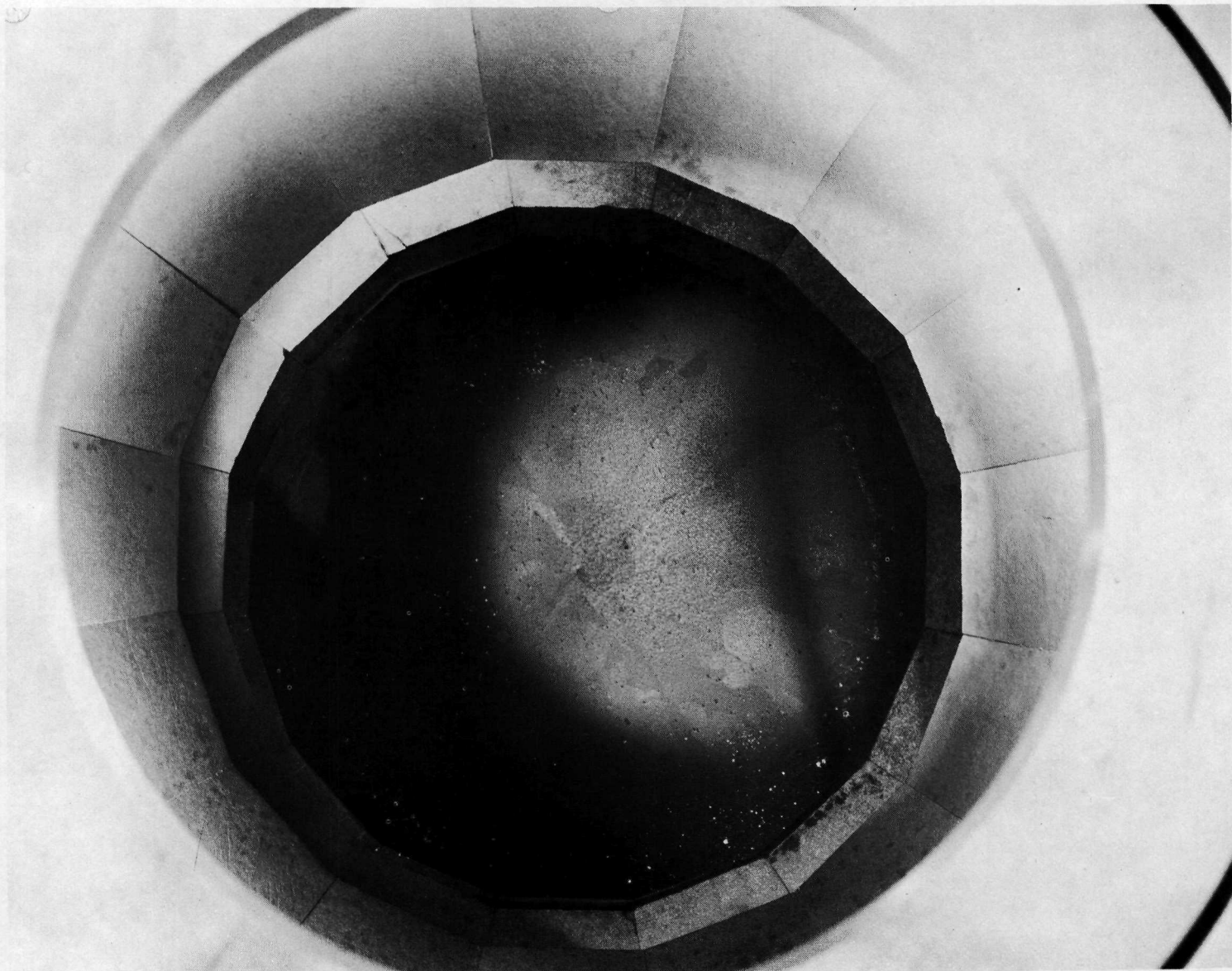


Figure 20. - Photograph of tank interior after test.